

# Azimuthal Transverse Single-Spin Asymmetries of Charged Pions Within Jets from Polarized pp Collisions at $\sqrt{s} = 200$ GeV

Ting Lin, for STAR Collaboration

Texas A&M University

BNL Nuclear Physics Seminar, June 30 2020



TEXAS A&M  
UNIVERSITY®

Supported in part by

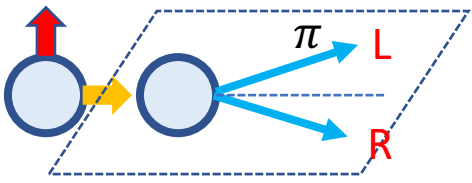


U.S. DEPARTMENT OF  
**ENERGY**

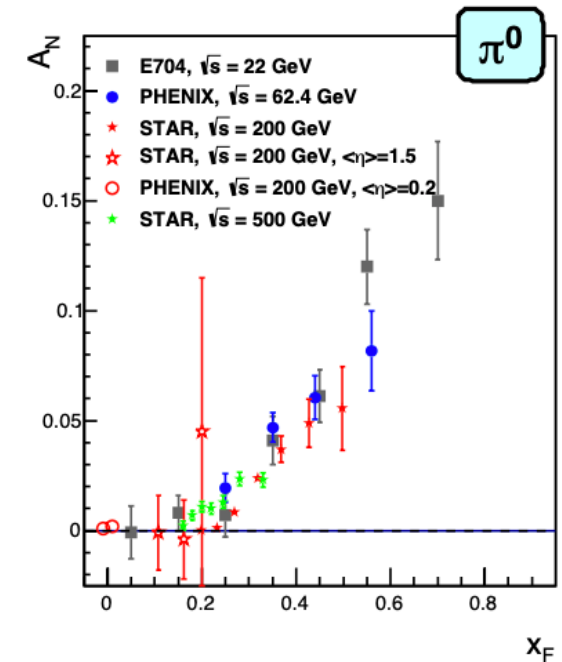
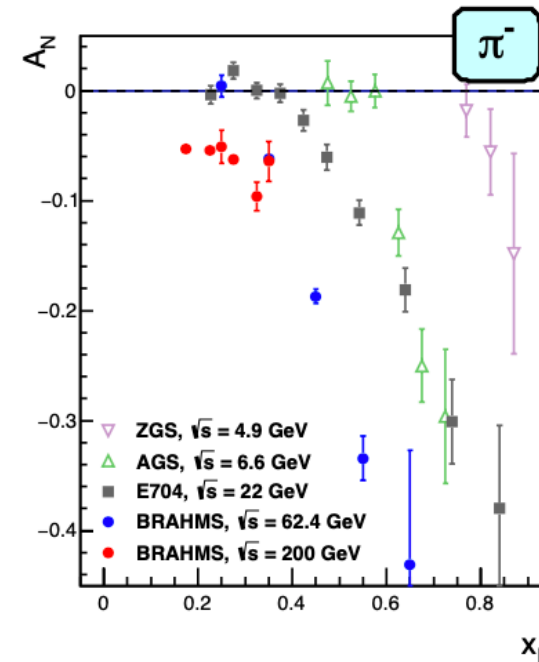
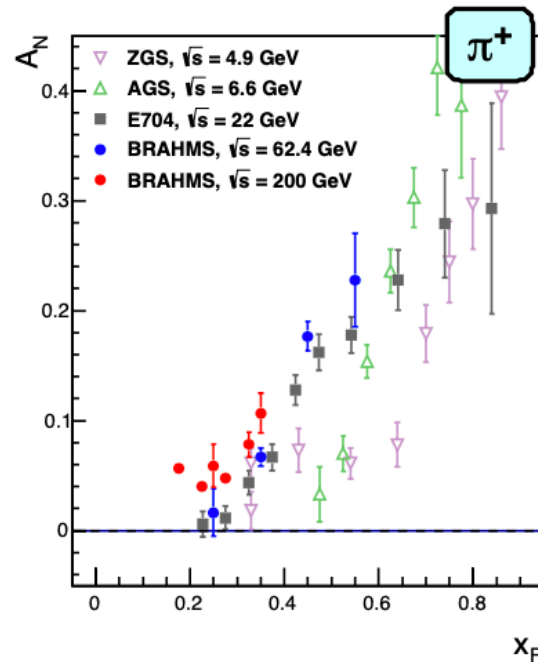
Office of  
Science

# Challenges in Transverse Single-Spin Asymmetry

- Large transverse single-spin asymmetry ( $A_N$ ) has been measured in transversely polarized proton-proton collisions;
- pQCD predicts very small asymmetries in the hard scattering process;
- Twist-3 and transverse momentum dependent (TMD) frameworks are developed to describe this transverse spin effect;



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

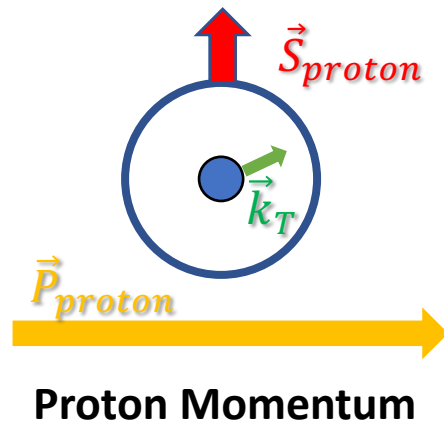


# Sivers and Collins Effect

## Sivers effect:

- In a transversely polarized proton, the constituent parton has a flavor dependent intrinsic momentum:

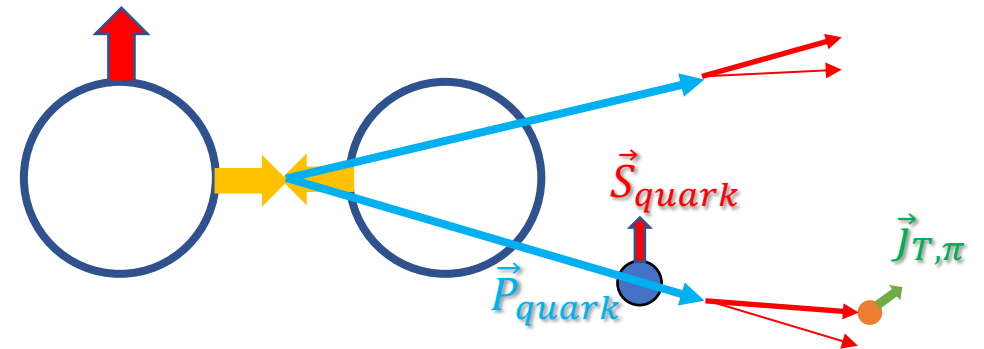
$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle \neq 0$$



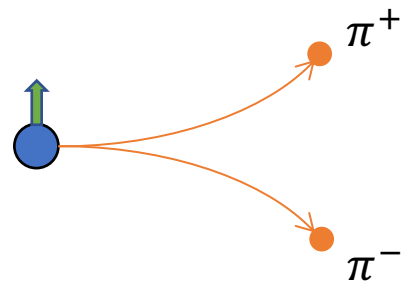
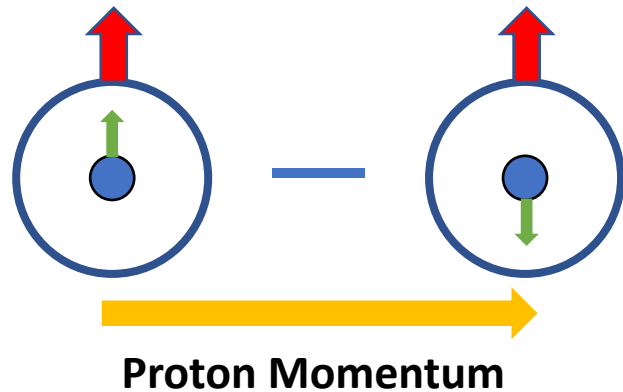
## Collins effect:

- Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction:

$$\langle \vec{S}_{quark} \cdot (\vec{P}_{quark} \times \vec{j}_{T,\pi}) \rangle \neq 0$$



# Collins Effect

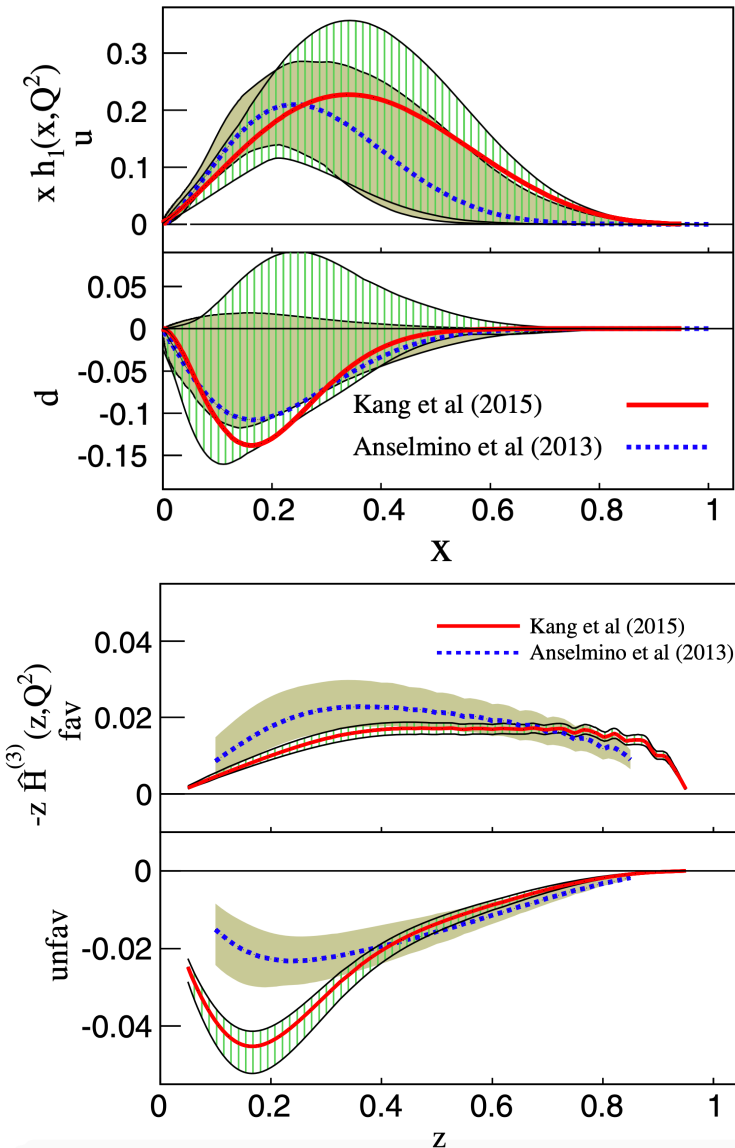


- Collins effect combines the **quark transversity** in the proton with the spin-dependent **Collins fragmentation function**, leading to azimuthal modulations of identified charged hadron yields about the jet axis;
  - Integral of transversity gives the nucleon tensor charge;
  - Difference of helicity and transversity has direct x-dependent connection to quark orbital angular momentum;
  - Collins fragmentation function in pp probes fundamental questions regarding factorization, universality, and evolution of TMDs.



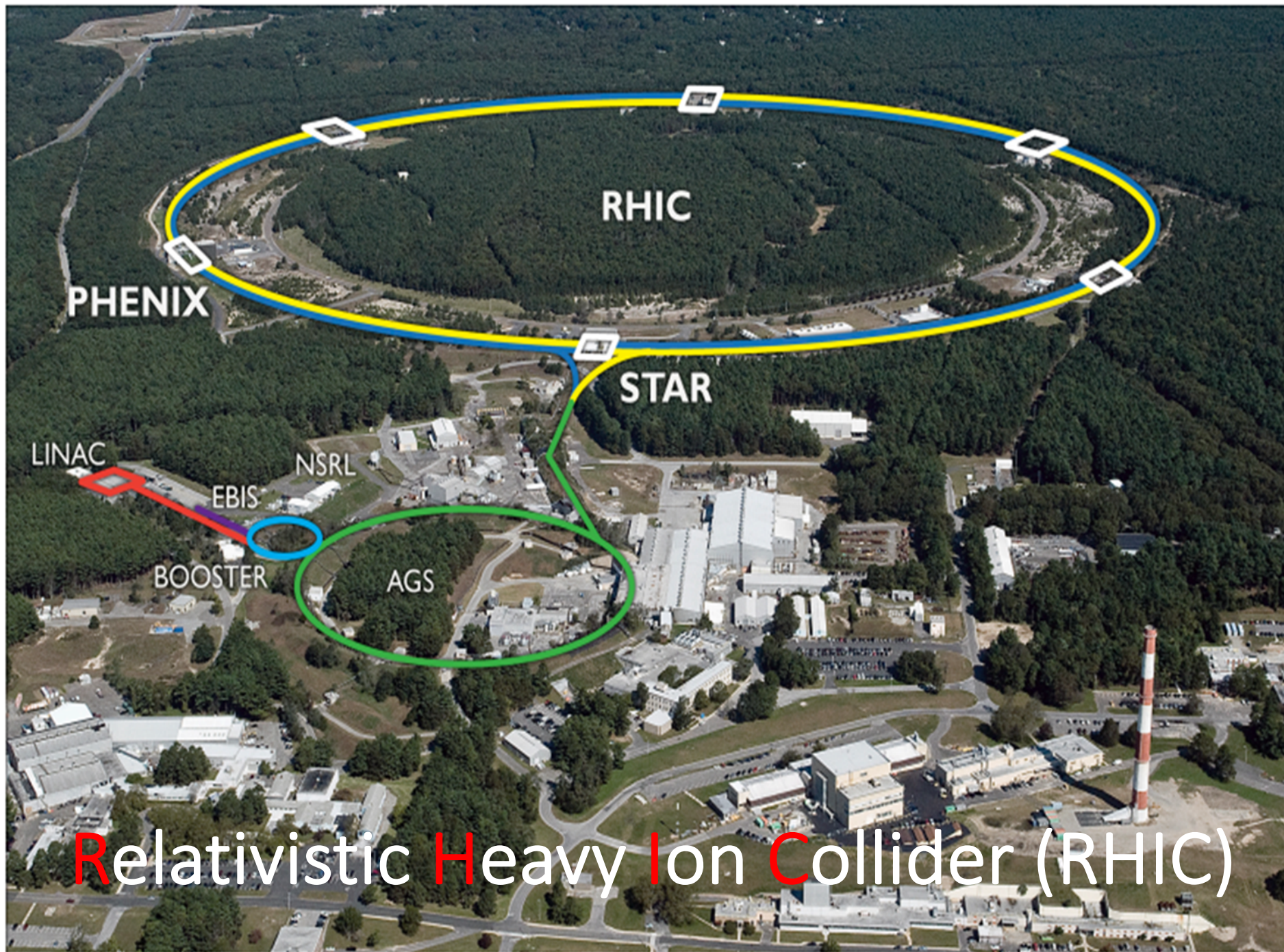
# Transversity

Phys. Rev. D 93, 014009 (2016)



- Transversity needs to couple with another chiral odd distribution:
  - Collins FF: correlates initial state quark spin to final state hadron's azimuthal distribution within the jets;
  - Interference fragmentation function (IFF): correlates quark polarization to azimuthal distribution of final state hadron pairs.
- Has much less data than unpolarized PDF and helicity;
- Before **STAR**, only observed in SIDIS combined with  $e^+e^-$ ;
- Several recent global analyses including:
  - Collins effect input from SIDIS:
    - JAM, arXiv:2002.08384 (2020)
    - PLB 803, 135347 (2020)
    - PRD 93, 014009 (2016)
    - PRD 92, 114023 (2015)
  - IFF input from SIDIS:
    - PRD 94, 034012 (2016)
  - IFF input from SIDIS and STAR pp:
    - PRL 120, 192001 (2018)
  - All show large uncertainties

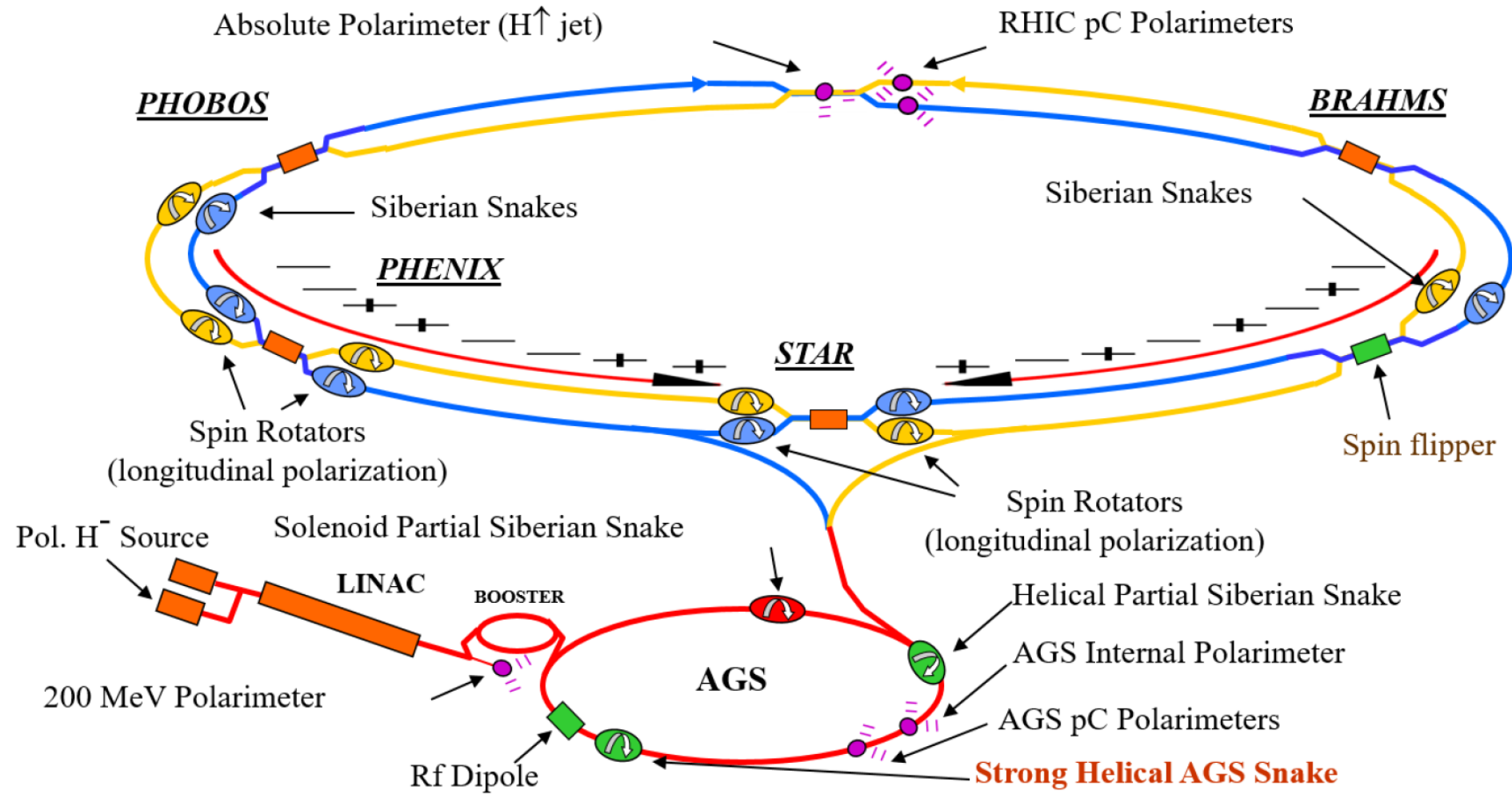




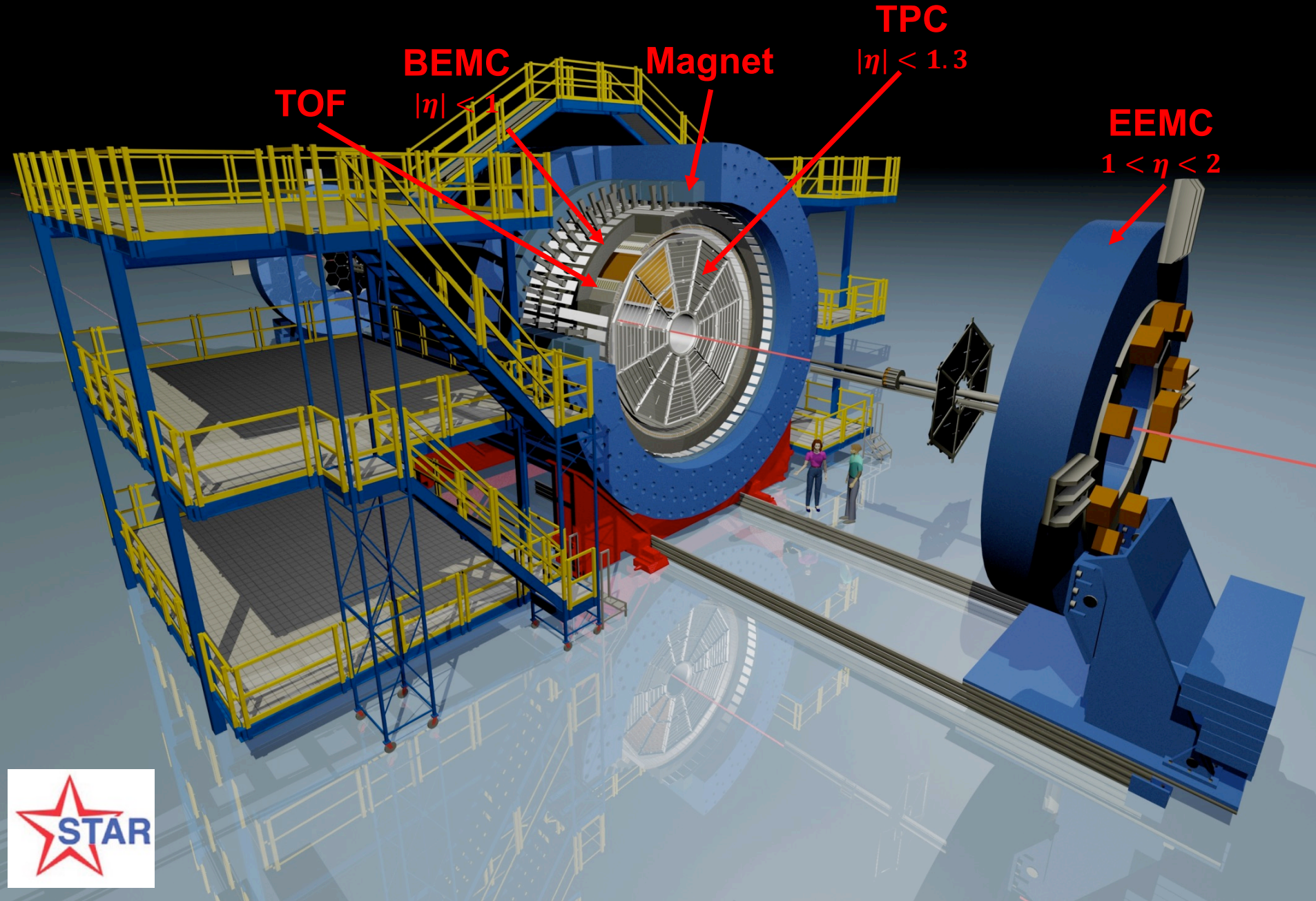
Relativistic Heavy Ion Collider (RHIC)



# Relativistic Heavy Ion Collider (RHIC)



# The Solenoidal Tracker At RHIC (STAR)



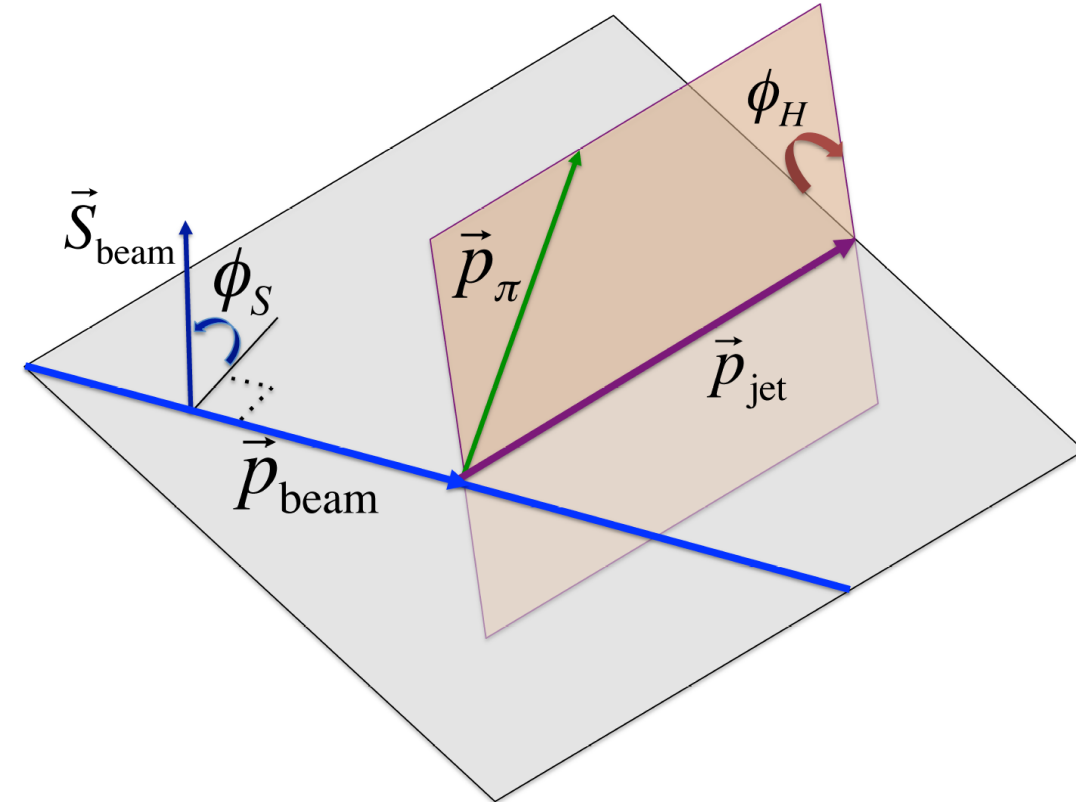
# Transverse Single-Spin Asymmetry

- For pions within jets, the spin dependent cross section is:

$$\begin{aligned} & d\sigma^\uparrow(\phi_S, \phi_H) - d\sigma^\downarrow(\phi_S, \phi_H) \\ & \sim d\Delta\sigma_0 \sin(\phi_S) \\ & + d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) \\ & + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H) \end{aligned}$$

- Different modulations of the transverse single-spin asymmetry can be isolated and studied:

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)}$$



Phys. Rev. D 97, 032004 (2018)  
Phys. Rev. D 83, 034021 (2011)

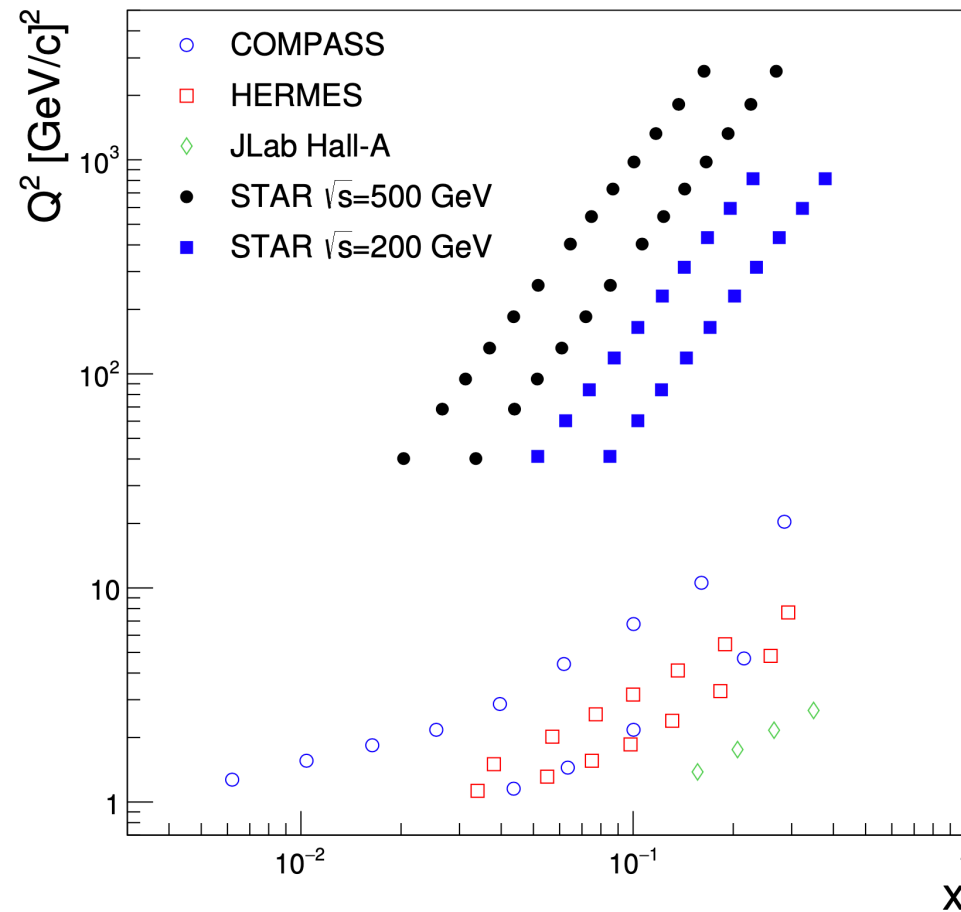
# Collins Effect in pp

$$A_{UT}^{\sin(\varphi_S - \varphi_H)} \propto \frac{\sum_{a,b,c} h_1^a(x_1, \mu) f_b(x_2, \mu) \sigma_{ab \rightarrow c}^{\text{Collins}} H_{1,h/c}^\perp(z_h, j_T; Q)}{\sum_{a,b,c} f_a(x_1, \mu) f_b(x_2, \mu) \sigma_{ab \rightarrow c}^{\text{unpol}} D_{h/c}(z_h, j_T; Q)}$$

Kang et al, JHEP 11, 068 (2017) and PLB 774, 635 (2017)

- Collins effect in pp involves a mixture of collinear and TMD factorization
  - Initial jet production involves the collinear transversity  $h_1^a$
  - Polarized quark then fragments according to the TMD Collins fragmentation function  $H_{1,h/c}^\perp$
- Cleaner kinematic separation of transversity and TMD physics than SIDIS, which convolutes the transversity TMD with the Collins FF

# Kinematic Coverage

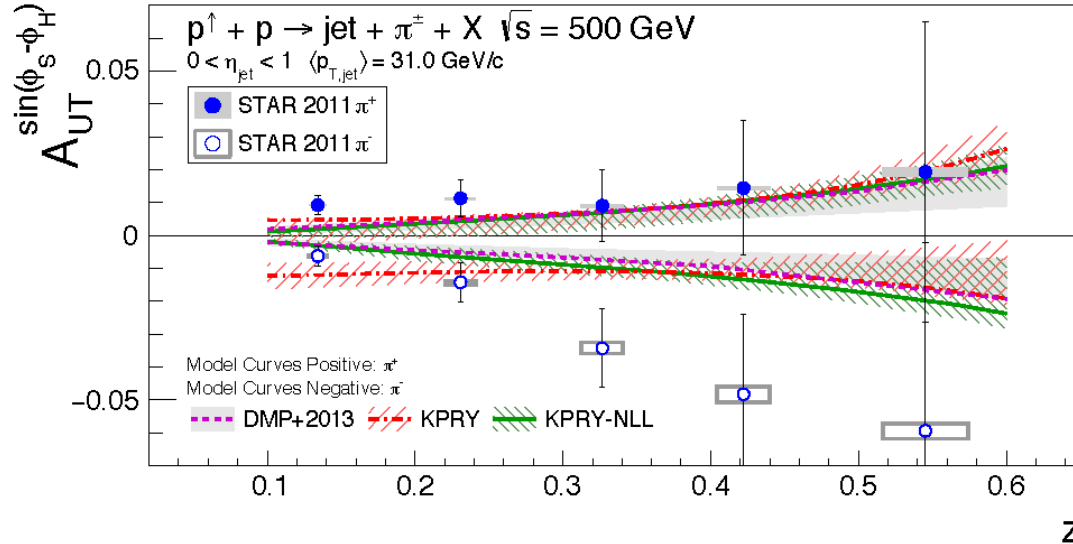


- STAR covers a similar range in momentum fractions ( $x$ ) to that of SIDIS results with much higher  $Q^2$
- Collins effect in pp provide a direct probe of the Collins fragmentation function and enable the test of its evolution, universality and factorization breaking in the TMD formalism.



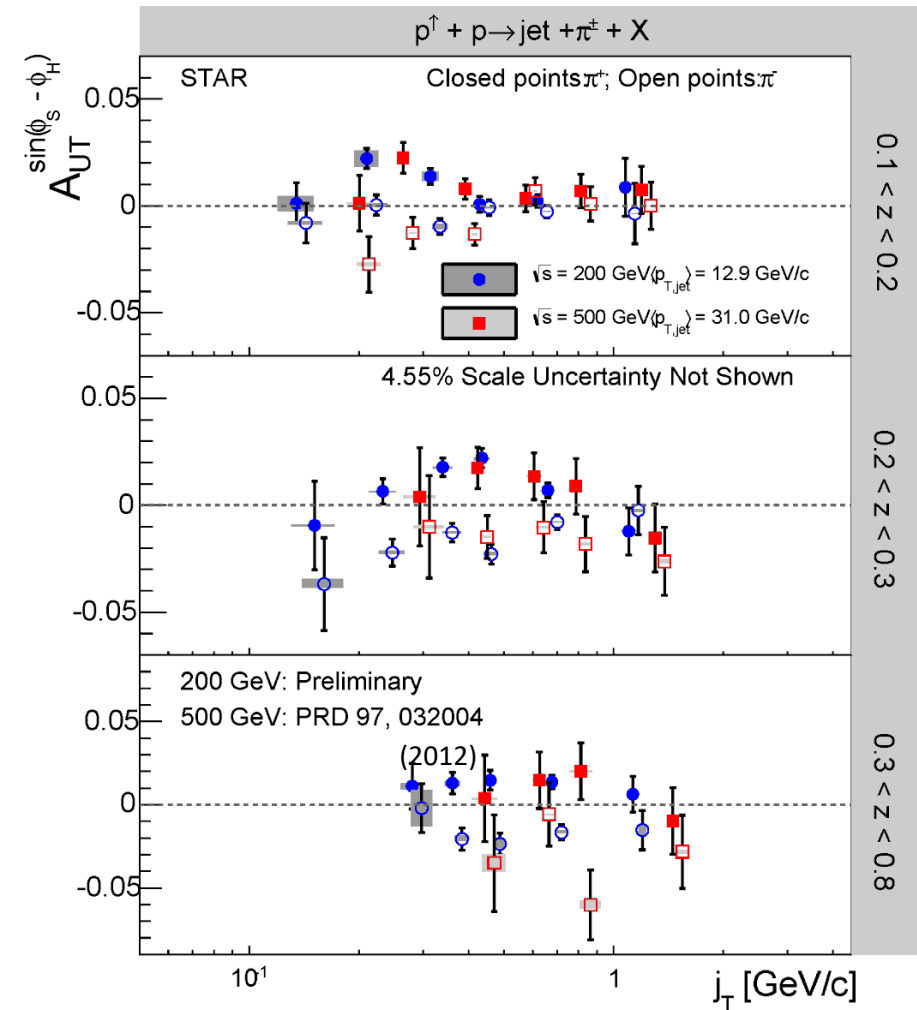
# Collins Asymmetry from STAR

pp500GeV: Phys. Rev. D 97, 032004 (2018)



- First Collins effect measurements in pp collisions are reasonably described by two recent calculations that combine the transversity distribution from SIDIS with the Collins FF from  $e^+e^-$  collisions
- Both 200 and 500 GeV pp results hint that the asymmetry peak shifts to higher  $j_T$  as  $z$  increases

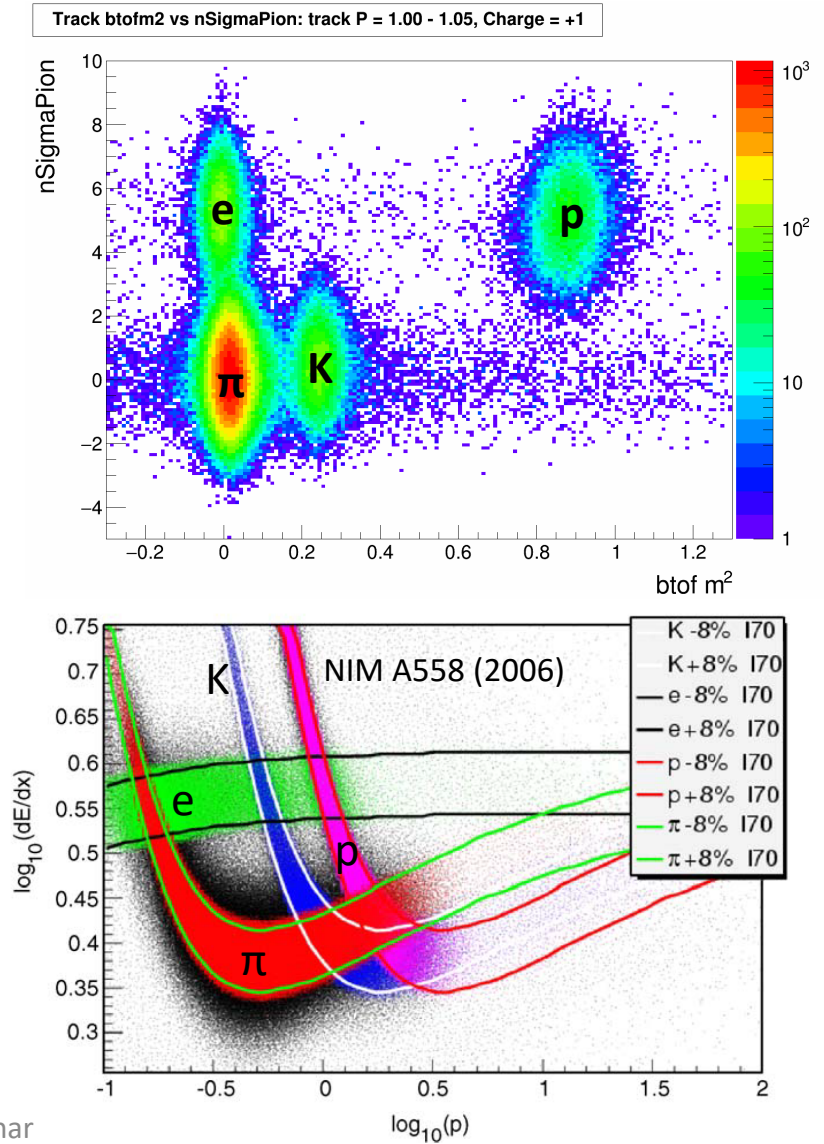
Spin2018: 2012 pp200GeV  
2011 pp500GeV





# 2015 Collins Analysis at STAR

- $52\text{pb}^{-1}$  transverse polarized p+p data at  $\sqrt{s} = 200$  GeV, twice as 2012;
- 57% averaged beam polarization;
- Particle identification from TPC and TOF;



# Jet Reconstruction

**Jet Levels**

**MC Jets**

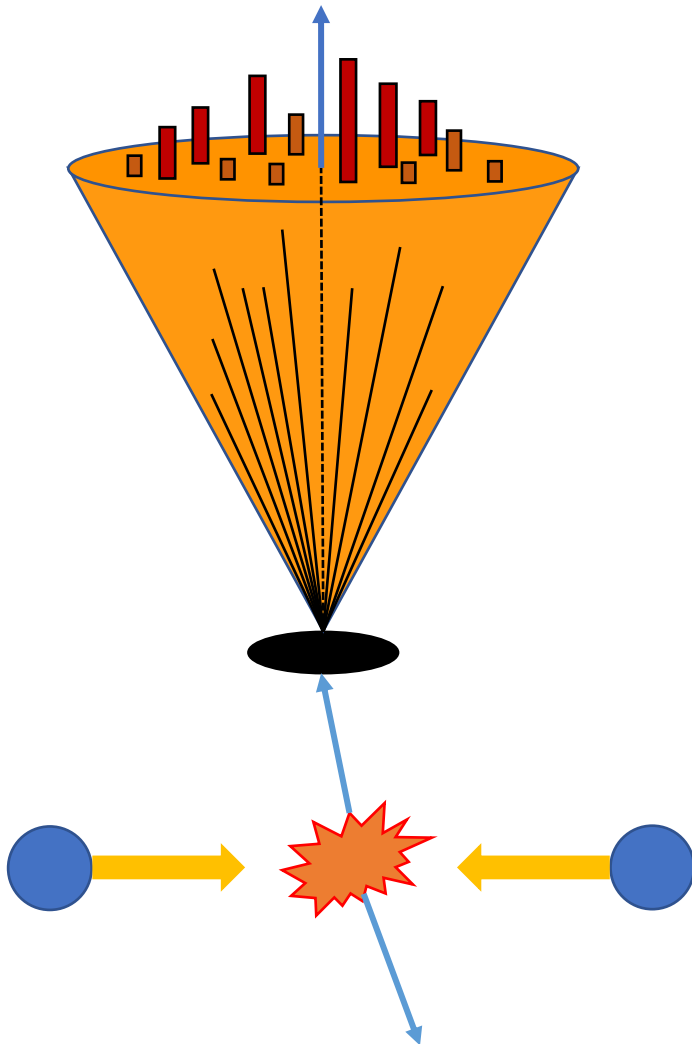
Detector

Particle

Parton

GEANT

PYTHIA



## Anti- $K_T$ Algorithm:

- Radius = 0.6
- Less sensitive to underlying event and pile-up effects
- Used in both data and simulation

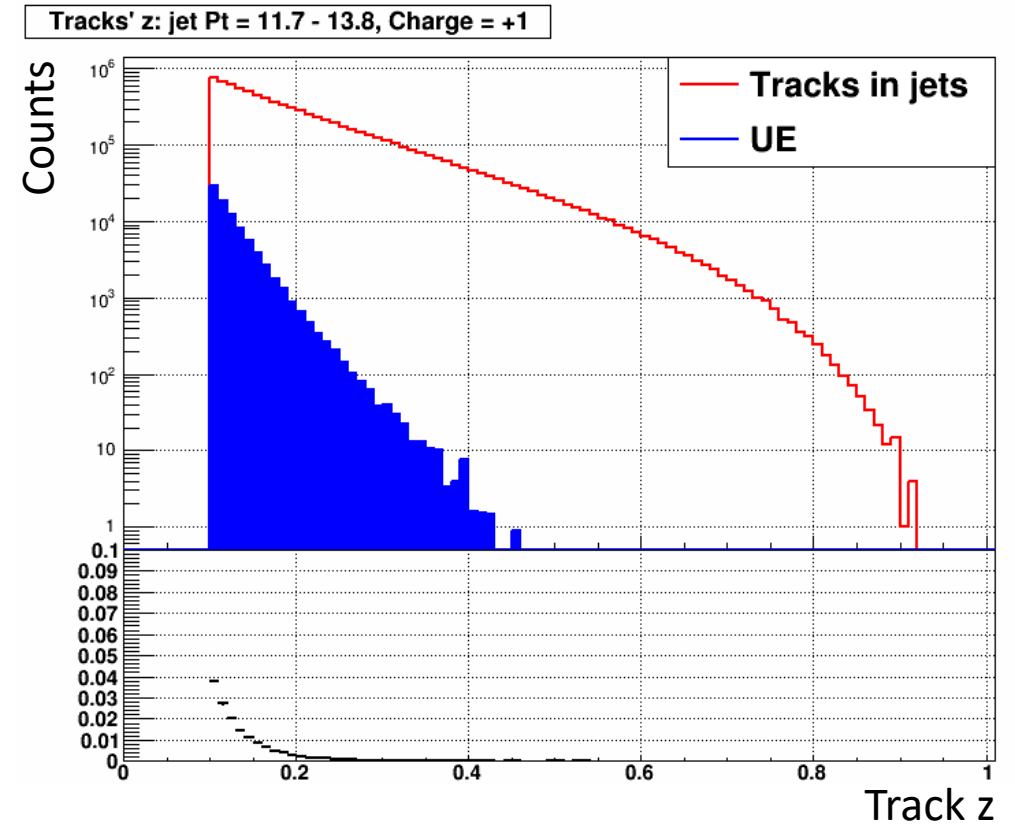
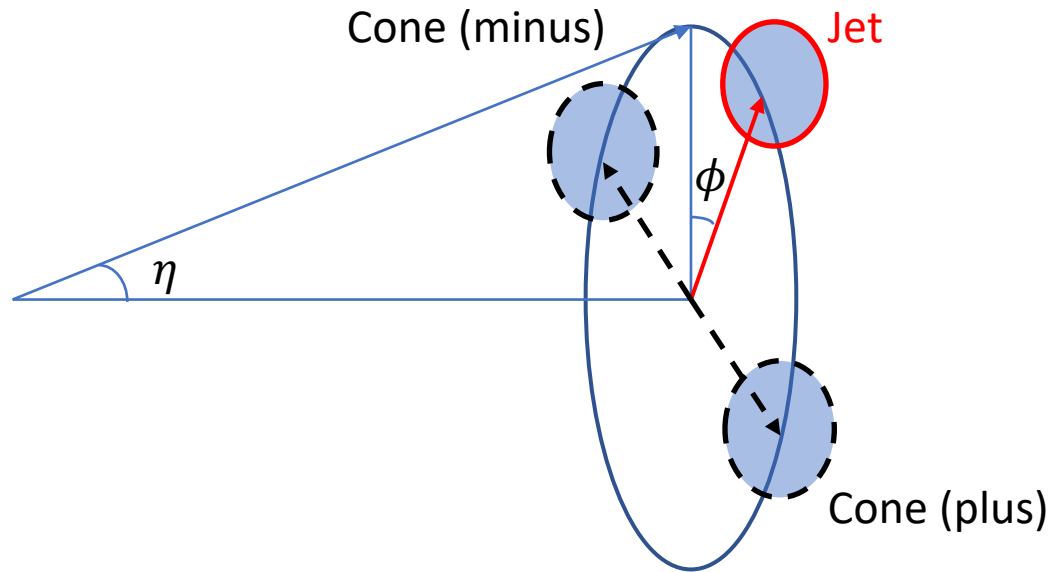
**Simulation:** PYTHIA 6.4 with STAR adjustment of Perugia 2012

## Three Simulation Levels :

- Parton – hard scattered partons involved in 2->2 hard scattering event from Pythia
- Particle – partons propagate and hadronize into stable and color-neutral particles
- Detector – detector response to the stable particles

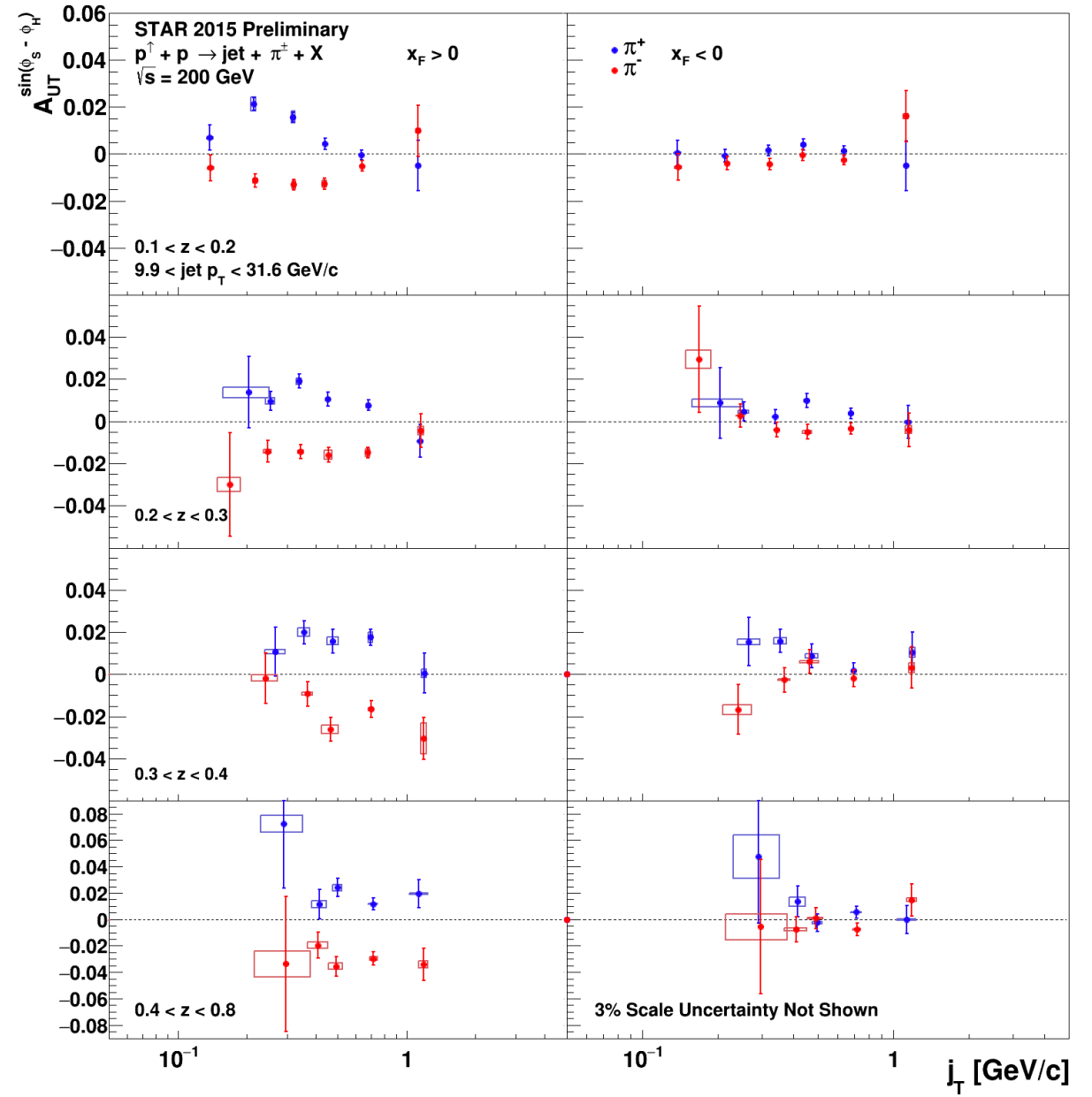
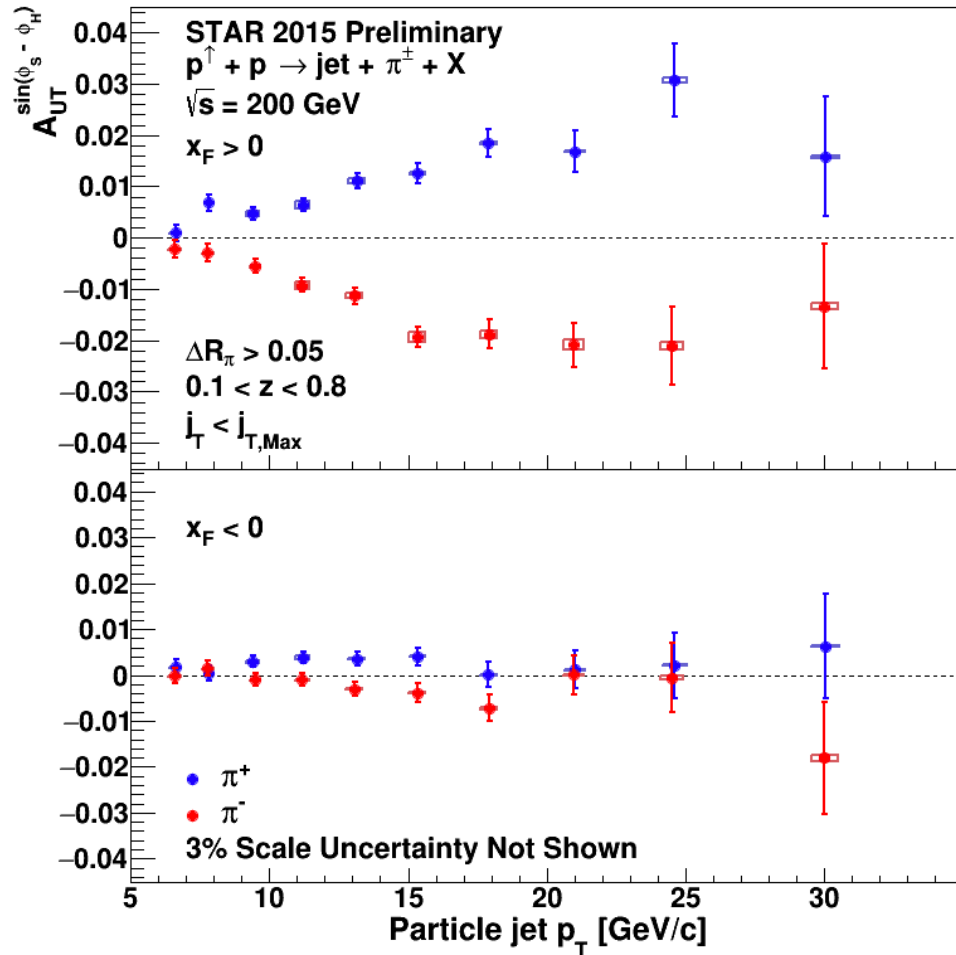
# 2015 Collins Analysis at STAR

Phys. Rev. D **100**, 052005 (2019)



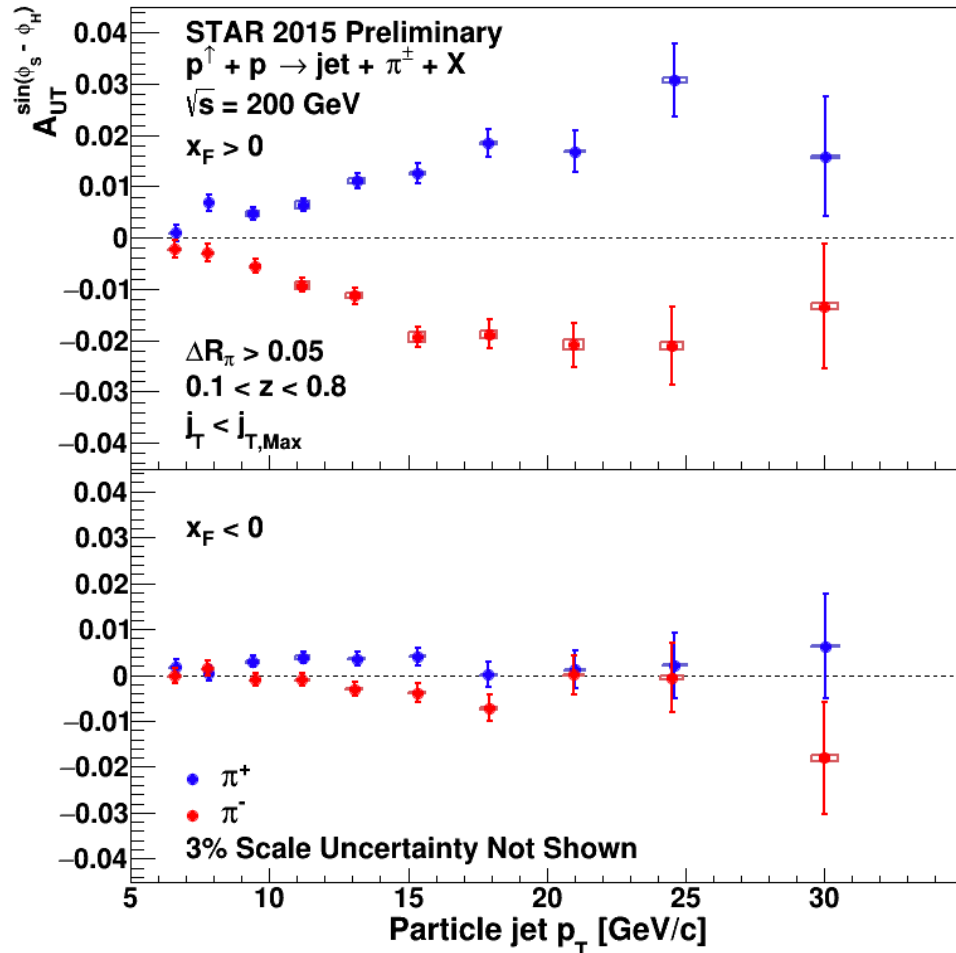
- Particle jet  $p_T$  values are corrected for underlying event activity measured using the off-axis cone method;
- Spin asymmetries are corrected for the dilution from the underlying event contribution;

# $\pi^\pm$ Azimuthal Distribution in Jets

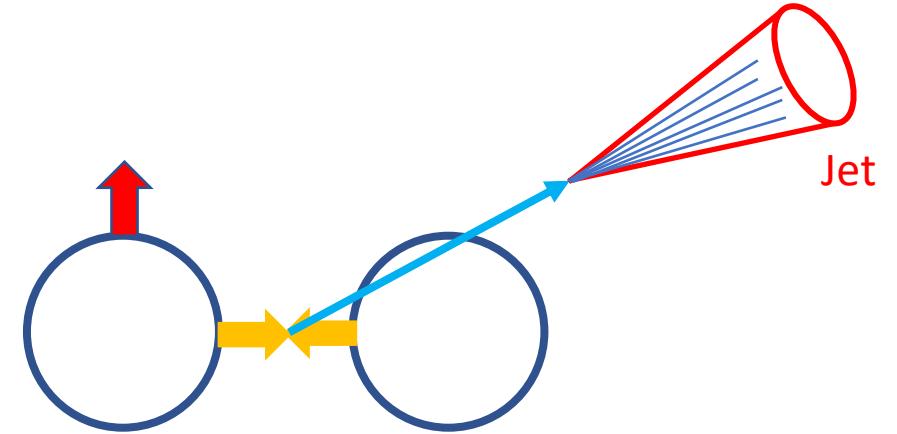


- New asymmetries agree with previously reported results, but have 30% smaller uncertainties;

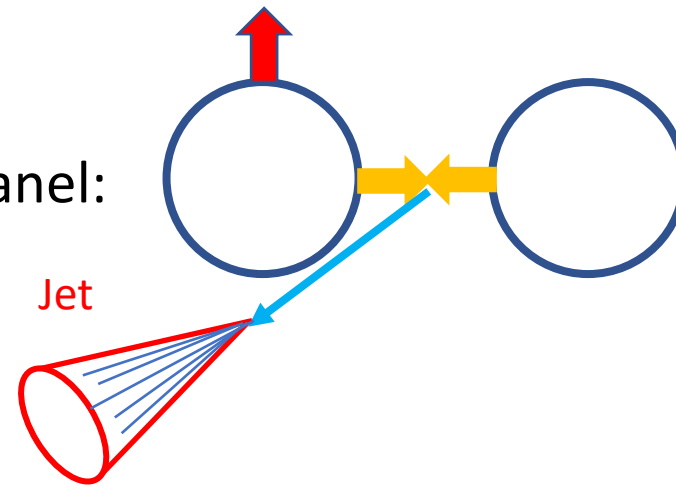
# $\pi^\pm$ Azimuthal Distribution in Jets



Top panel:

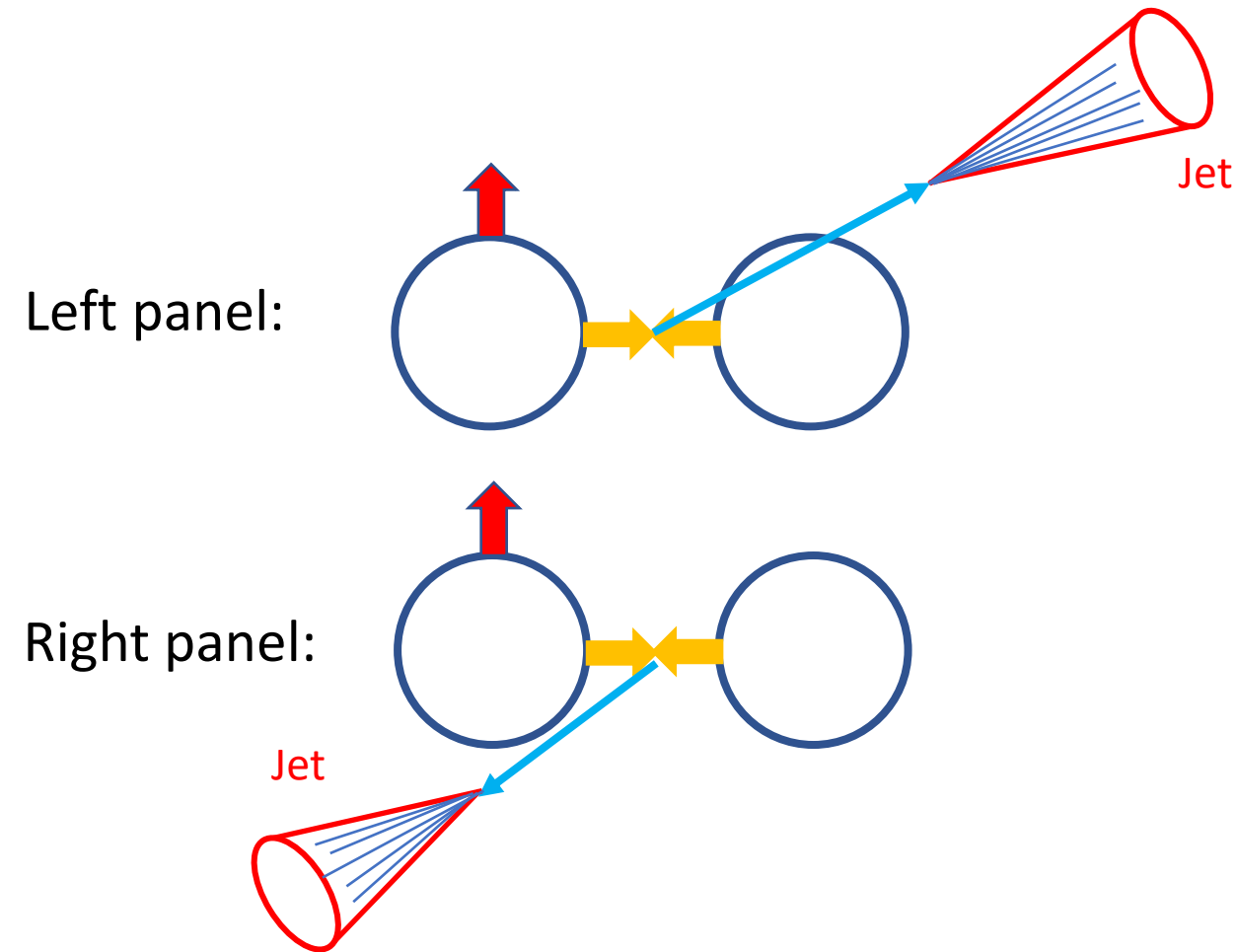


Bottom panel:

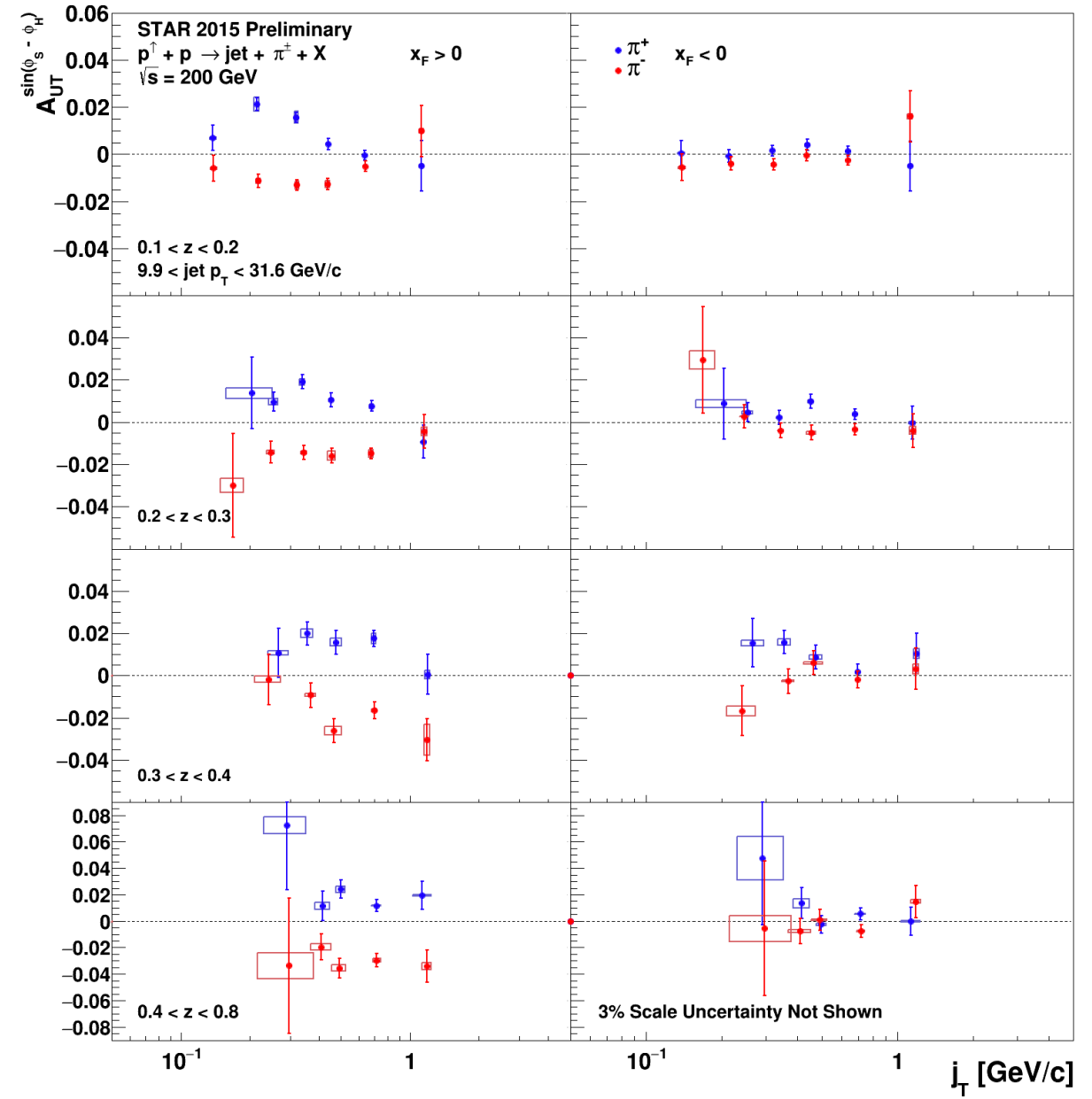


- New asymmetries agree with previously reported results, but have 30% smaller uncertainties;

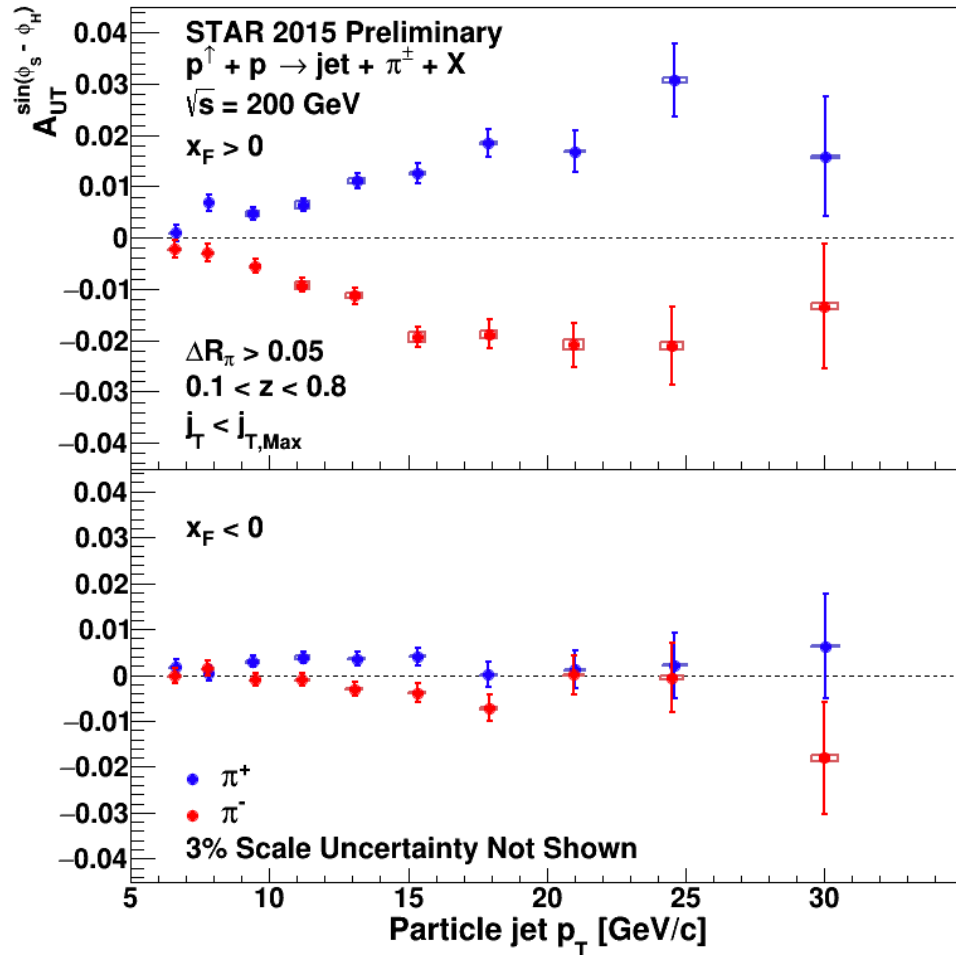
# $\pi^\pm$ Azimuthal Distribution in Jets



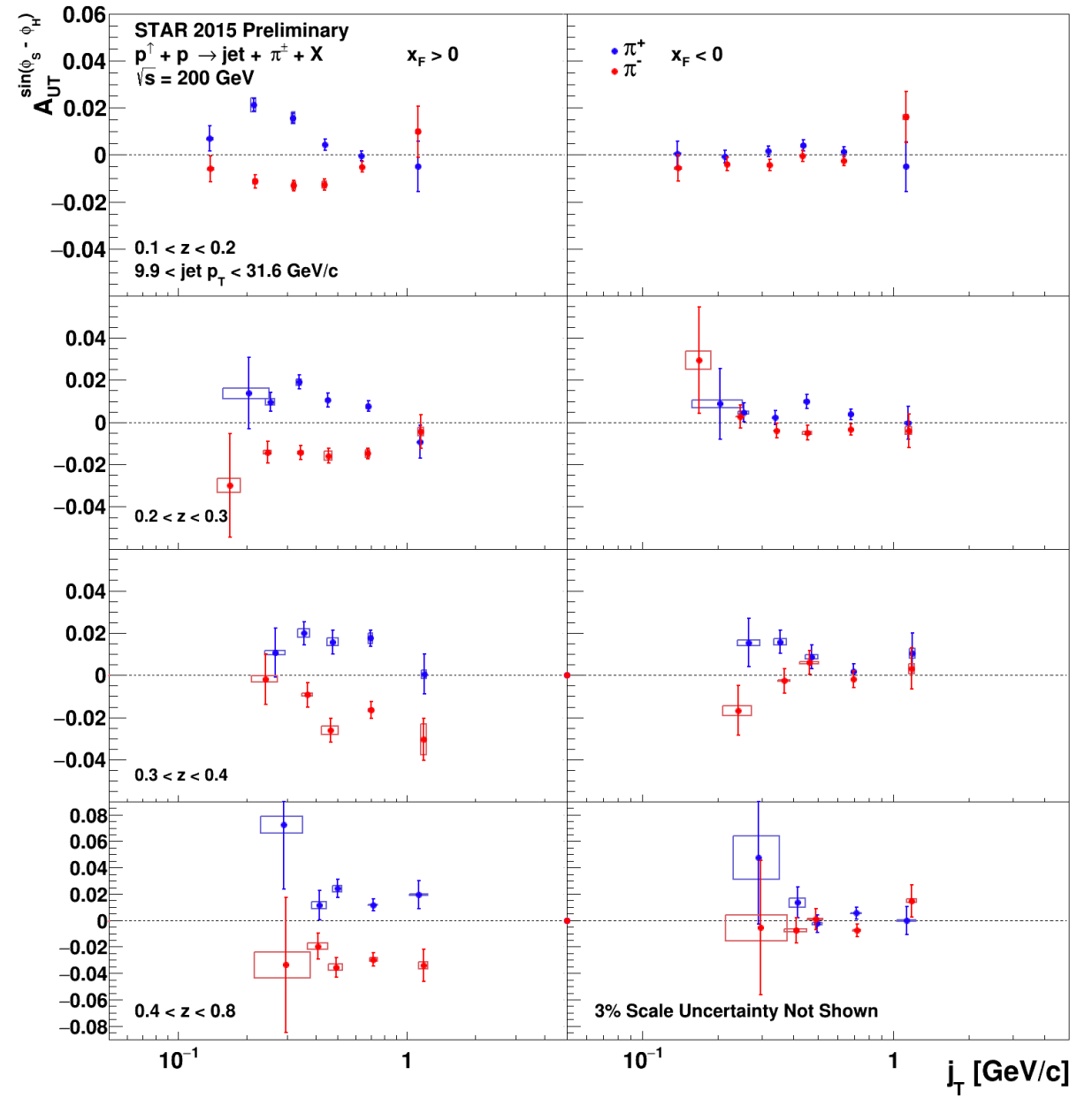
- New asymmetries agree with previously reported results, but have 30% smaller uncertainties;



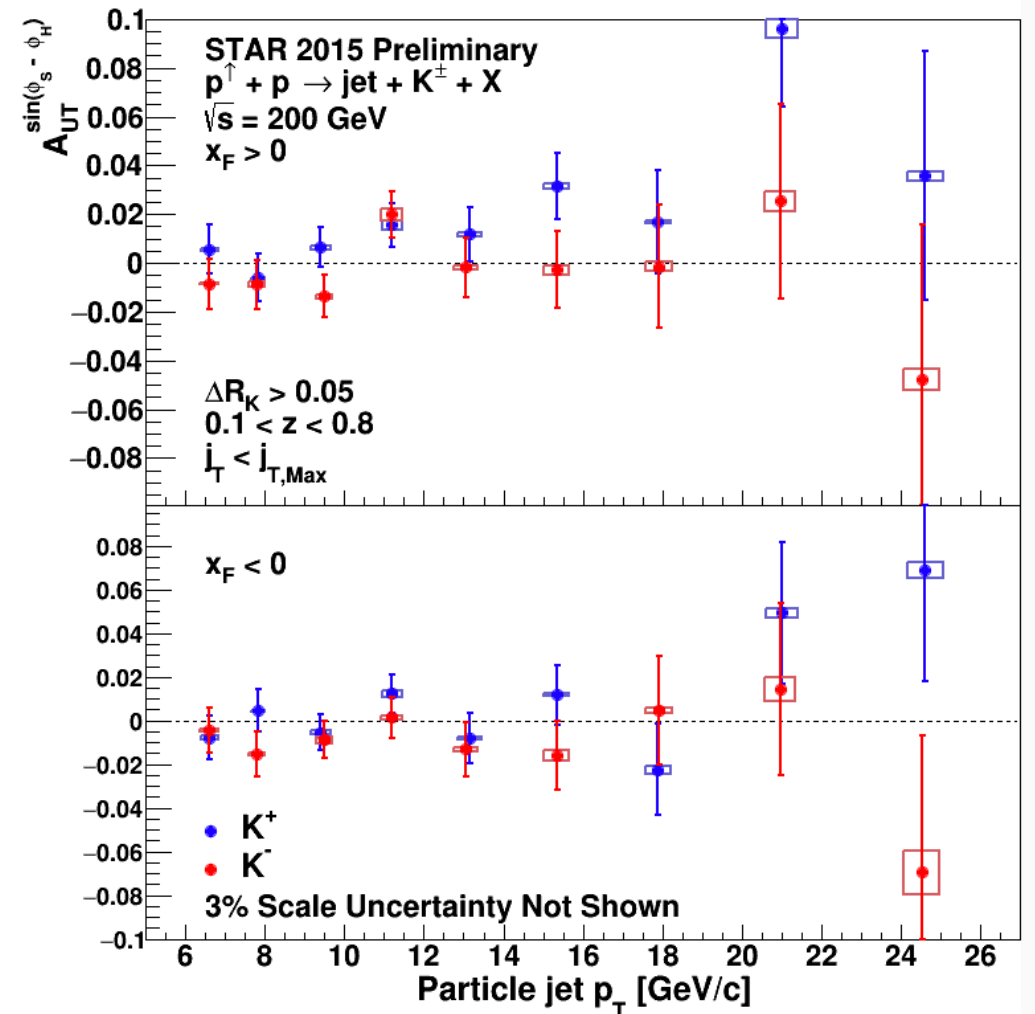
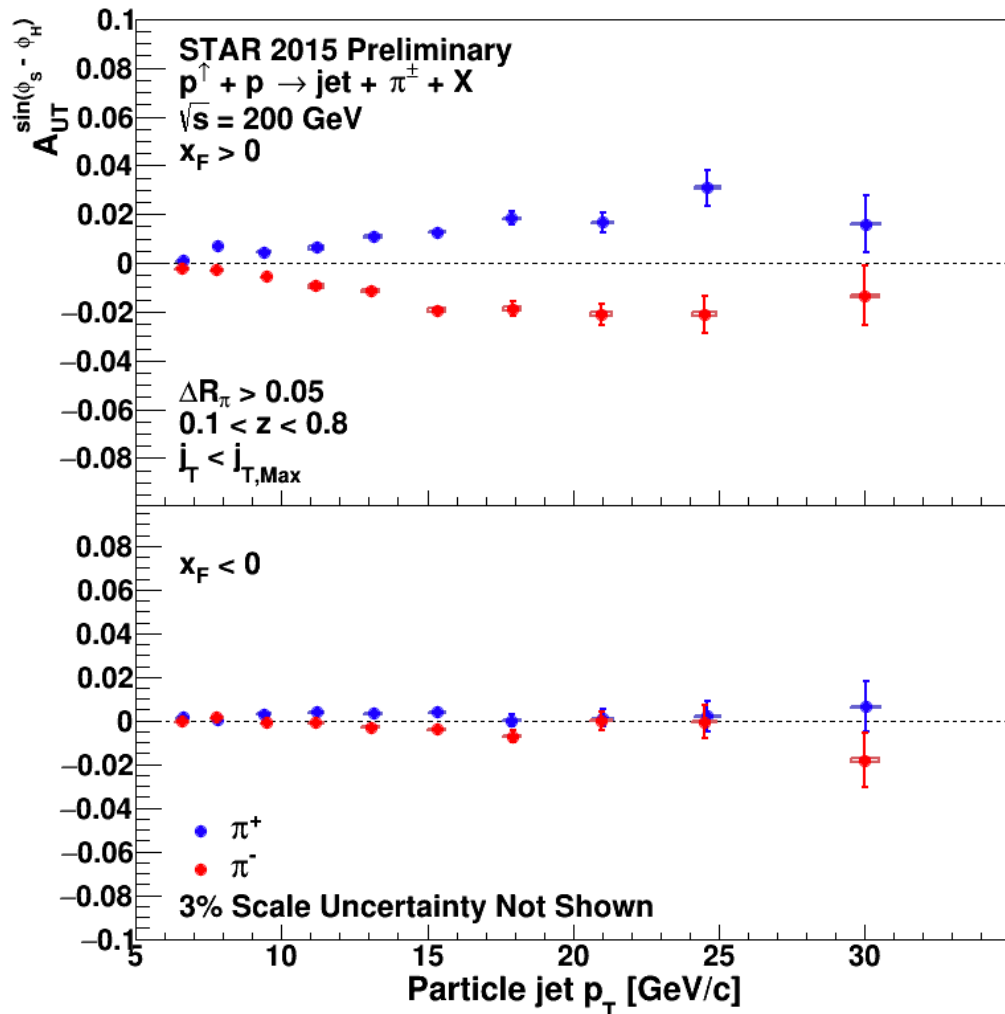
# $\pi^\pm$ Azimuthal Distribution in Jets



- Collinear transversity is probed most directly in the jet  $p_T$  and eta dependence;
- Collins TMD FF is sensitive to the  $(j_T, z)$  dependence.



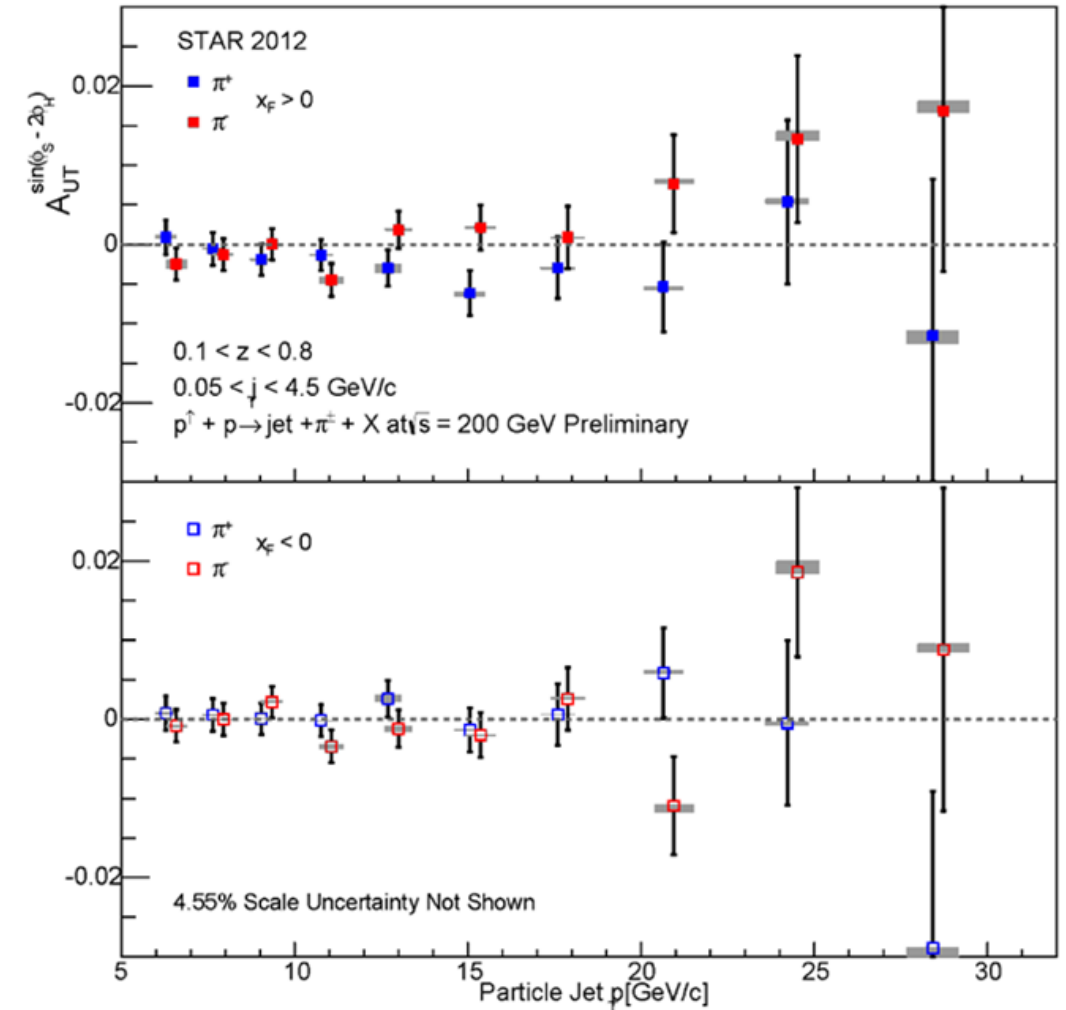
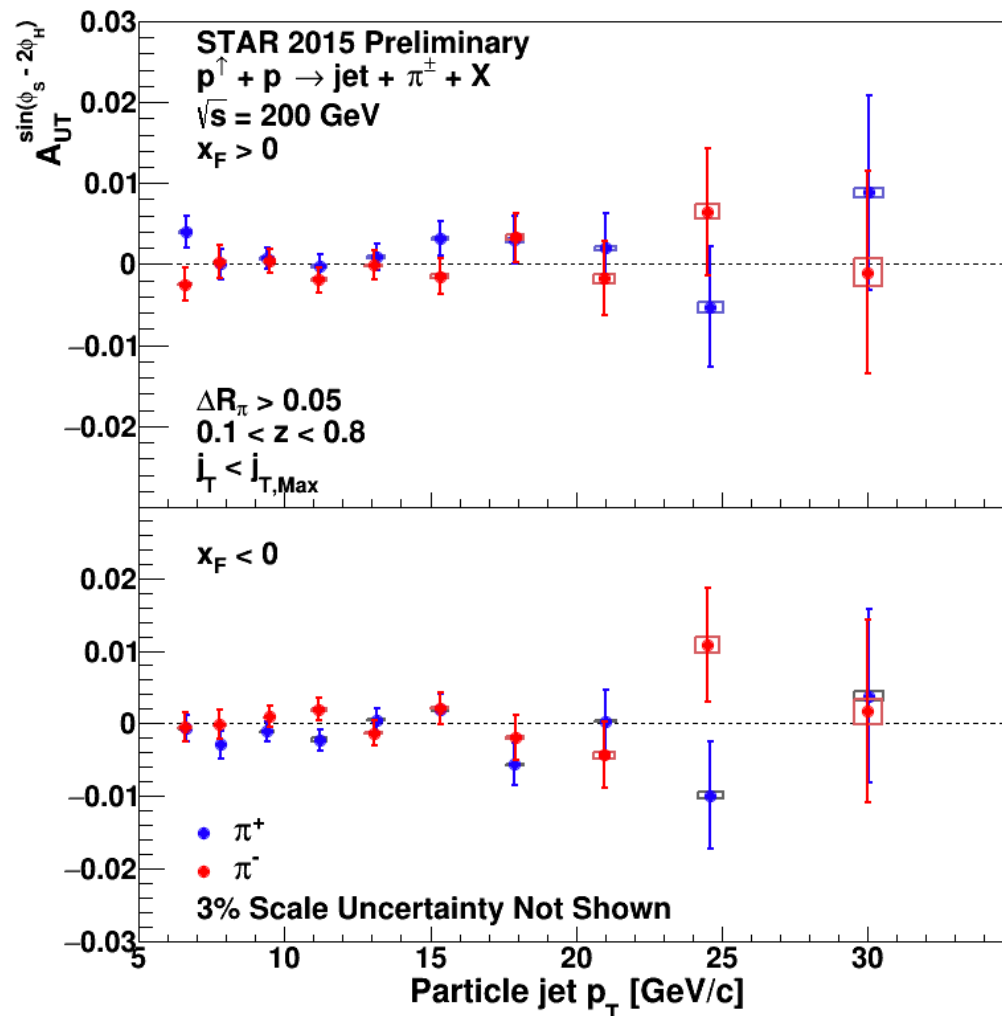
# $K^\pm$ Azimuthal Distribution in Jets



- $K^+$  shows positive asymmetries for forward jets, consistent within the currently large statistical uncertainties with the  $\pi^+$  asymmetries;

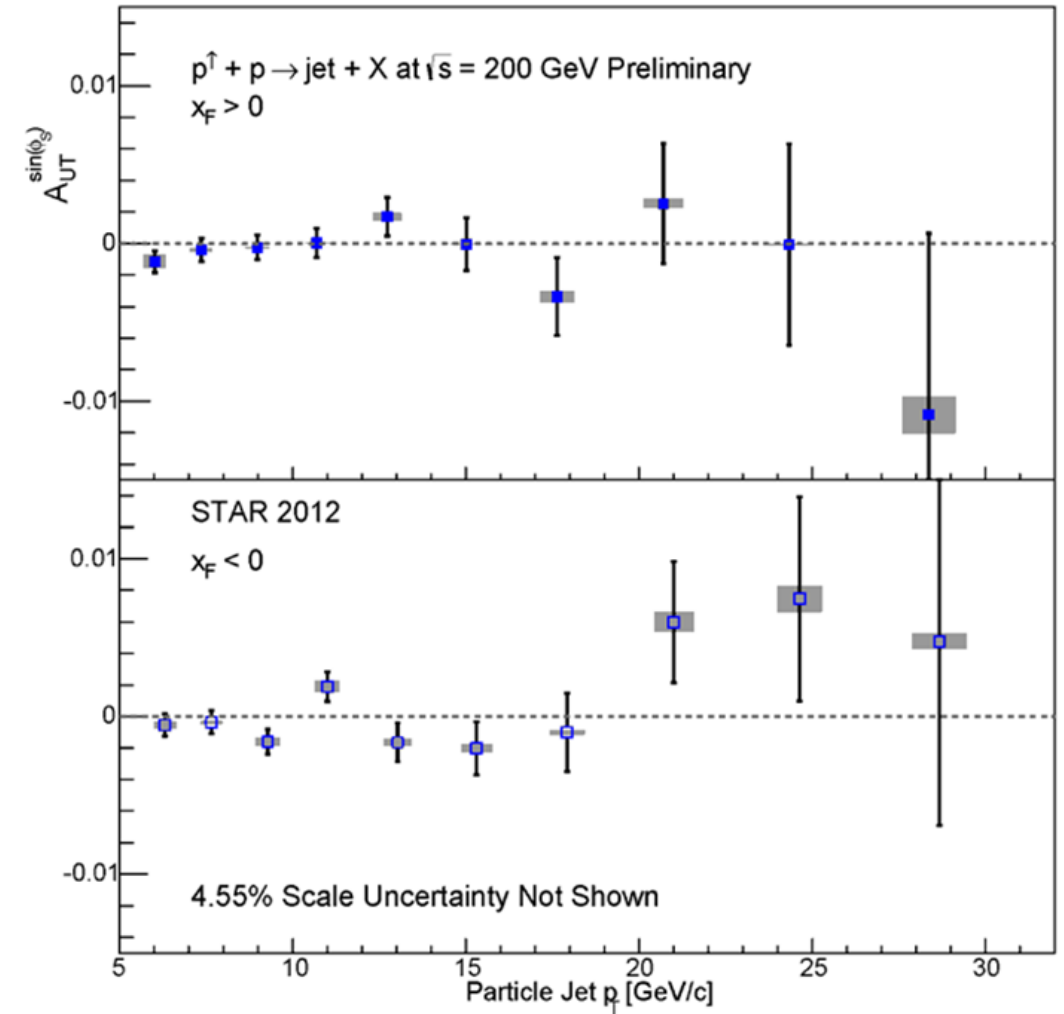
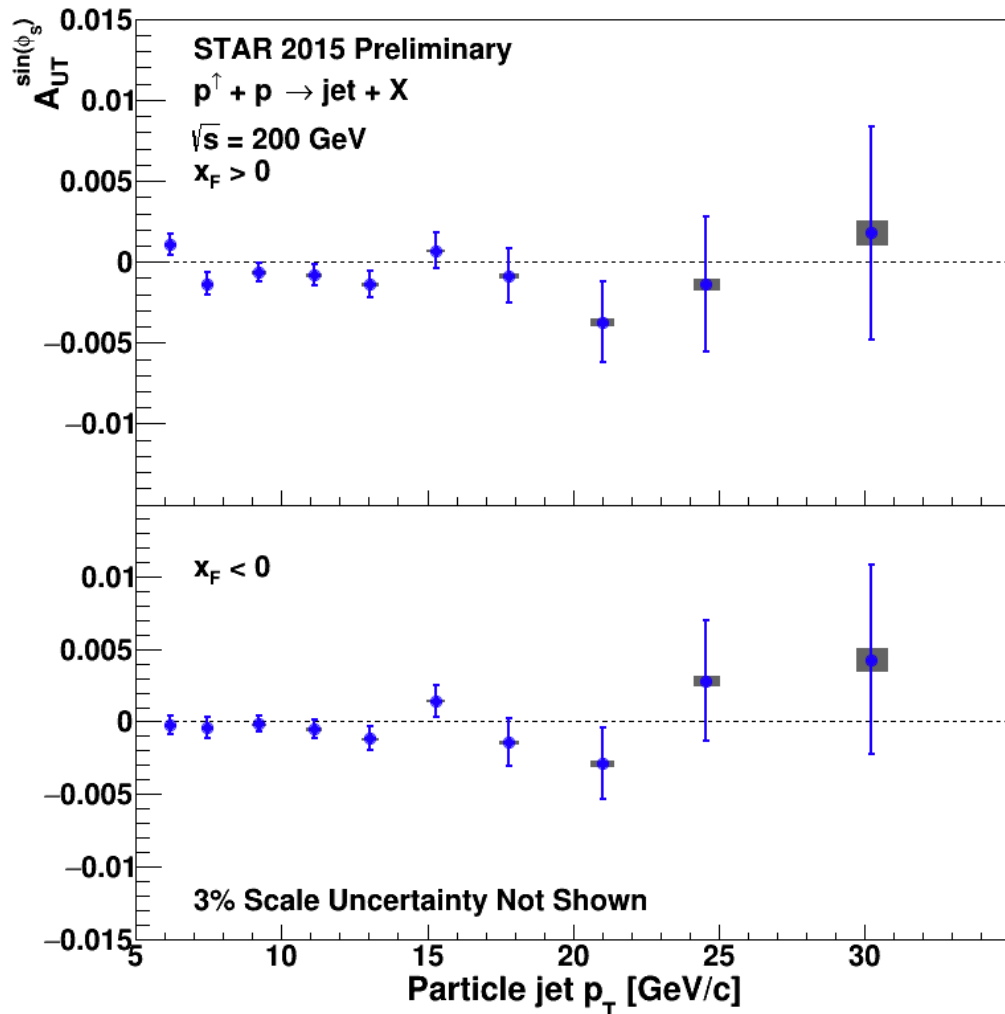


# Additional Modulations: “Collins-like” Effect



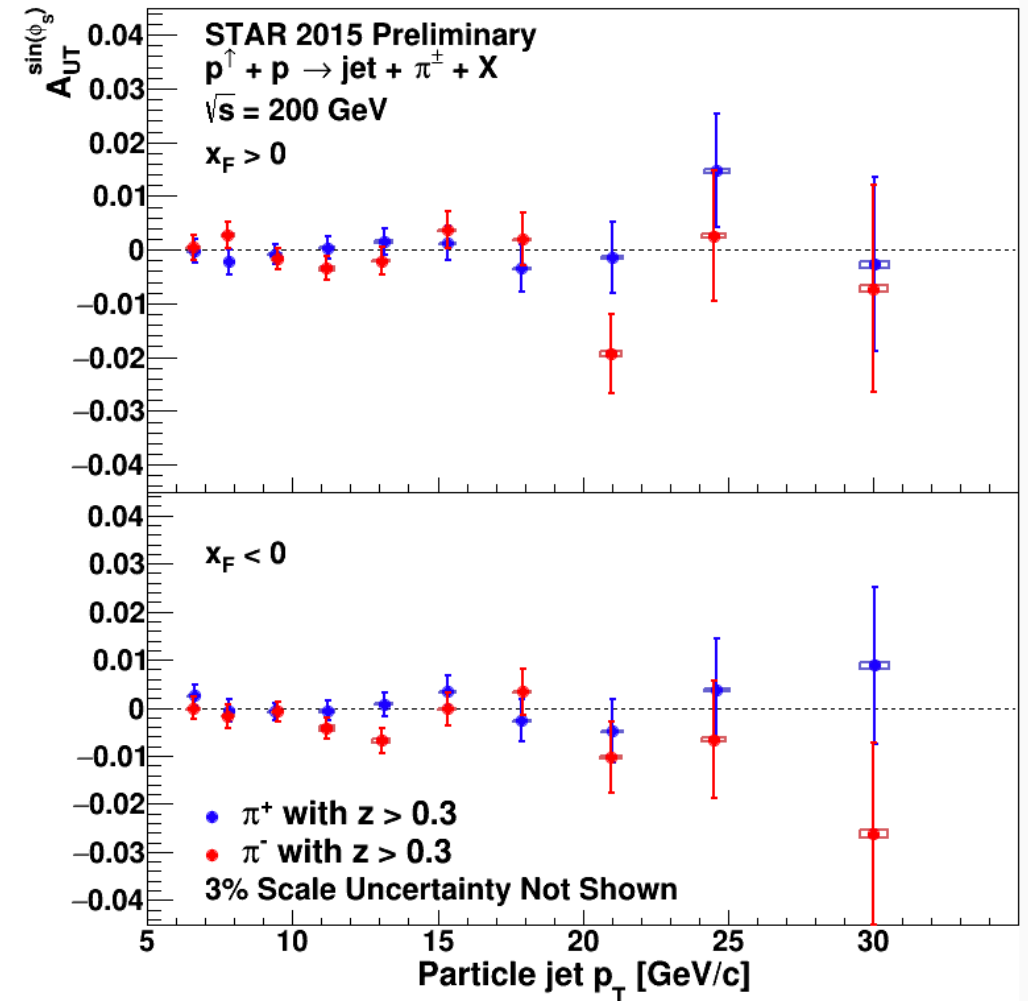
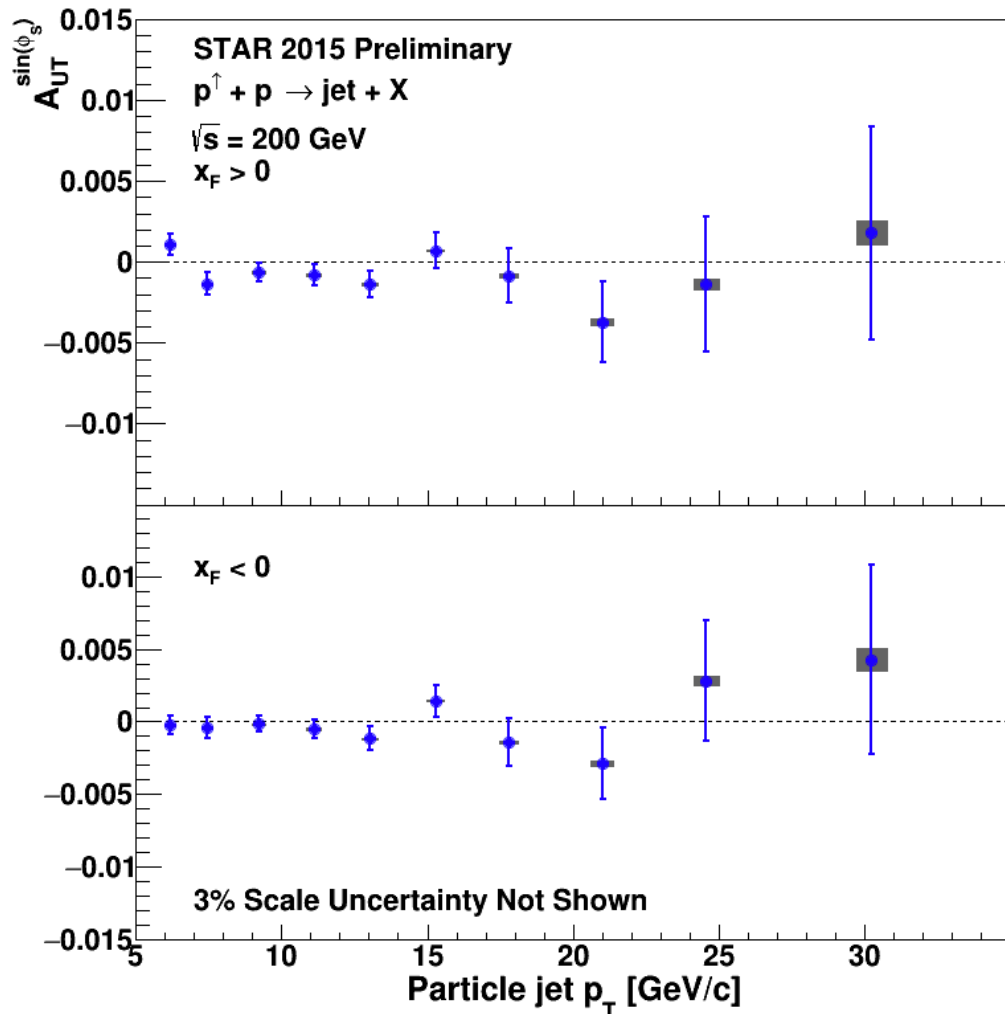
- Collins-like effect is sensitive to the linearly polarized gluons in a polarized proton;
- Even with higher precision in 2015, asymmetries are still consistent with zero;

# Additional Modulations: Inclusive Jet $A_N$



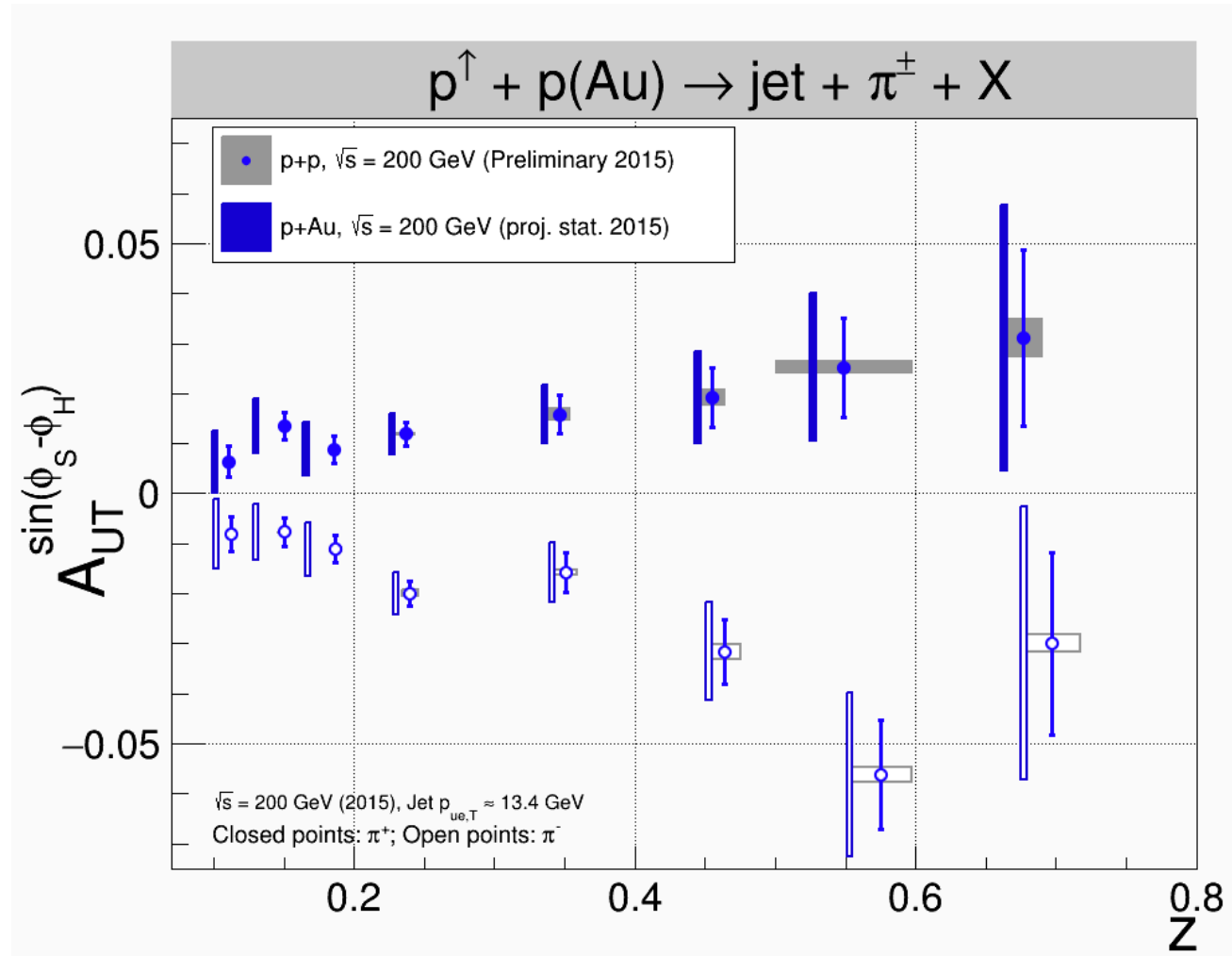
- Inclusive jet  $A_N$  is sensitive to the gluon Siverson function via the twist-3 correlators;
- Even with higher precision in 2015, asymmetries are still consistent with zero;

# Additional Modulations: Inclusive Jet $A_N$



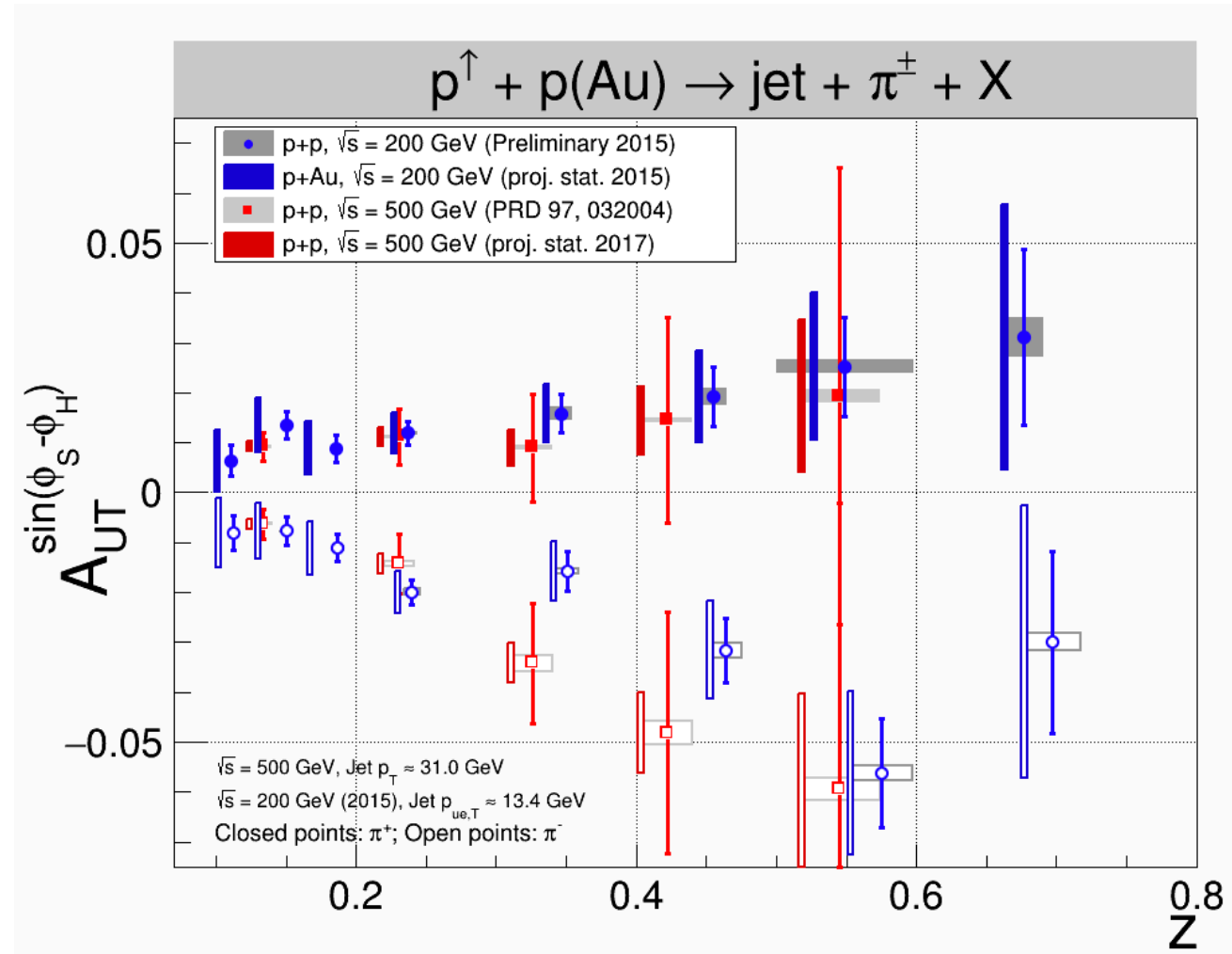
- Measure the jet  $A_N$  with  $\pi^\pm$  that carries large momentum fraction;
  - Attempt to enrich the u/d quark fractions
- Asymmetries are consistent with zero;

# More STAR Analysis Ongoing



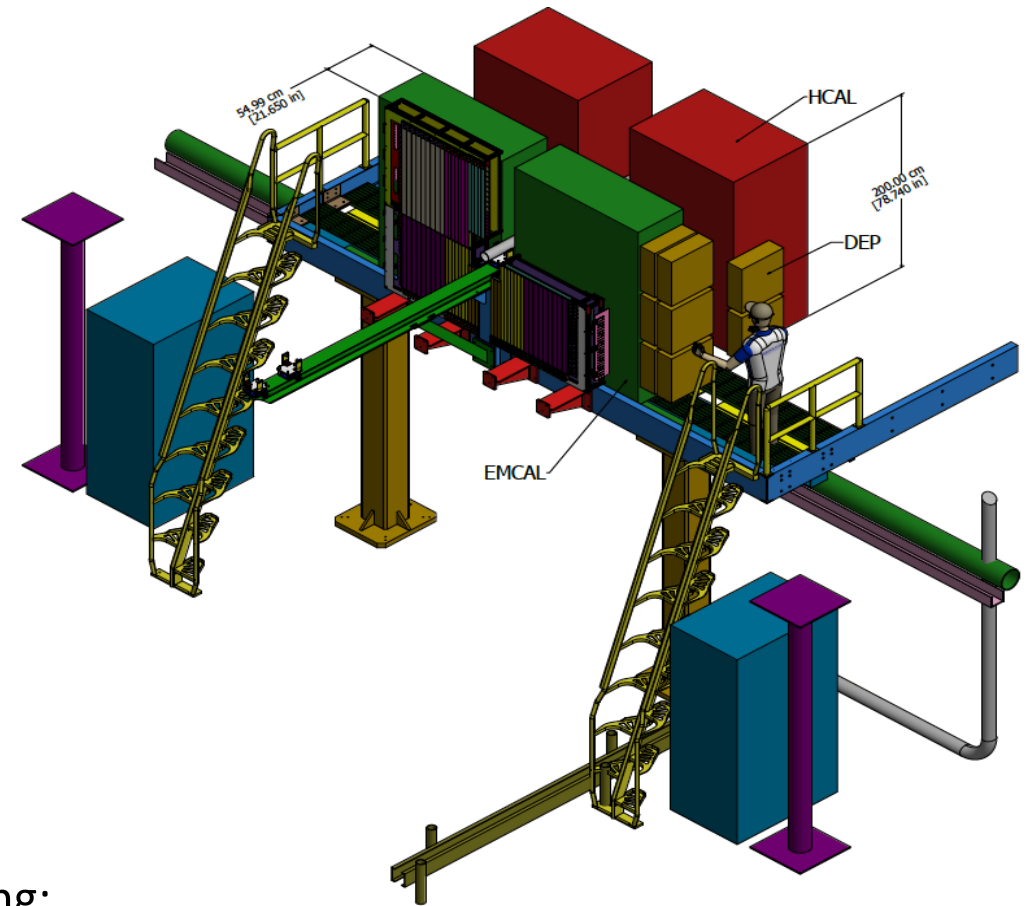
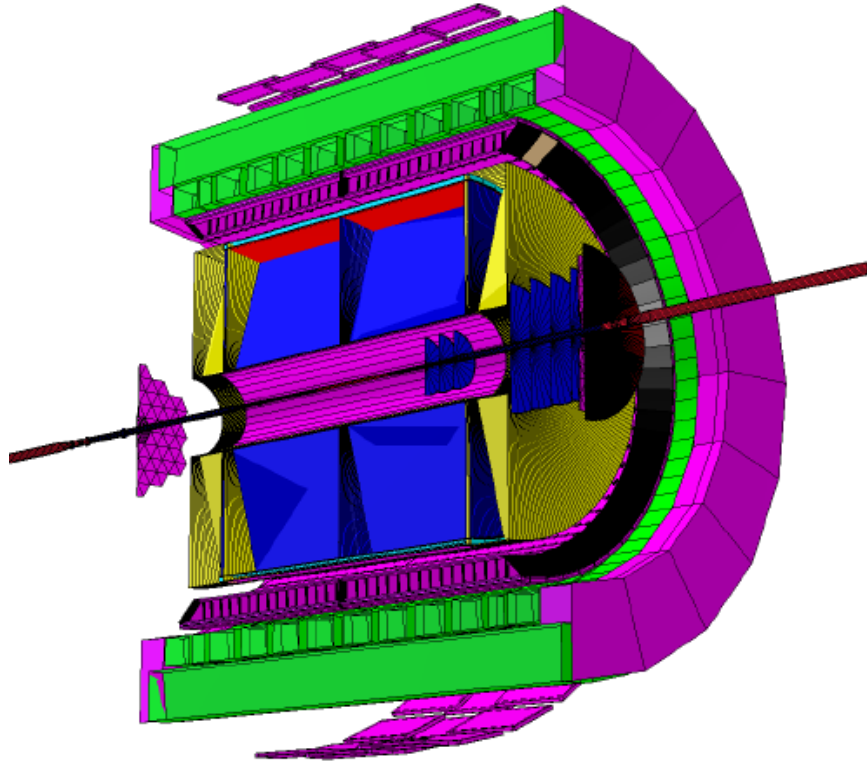
- Data under analysis from 2015 p+Au collisions at 200 GeV;

# More STAR Analysis Ongoing



- Data under analysis from 2015 p+Au collisions at 200 GeV;
- Also data from 2017 pp 510 GeV, which provides more precise measurement at higher  $Q^2$  and lower  $x$ ;

# Forward Upgrade Ongoing



- Si disks + Small Thin Gap Chambers (STGC) for tracking;
- Electromagnetic and hadronic calorimeters;
- Precision TMD measurements through jets at forward rapidity
  - Probe higher  $x$  quarks and lower  $x$  gluons

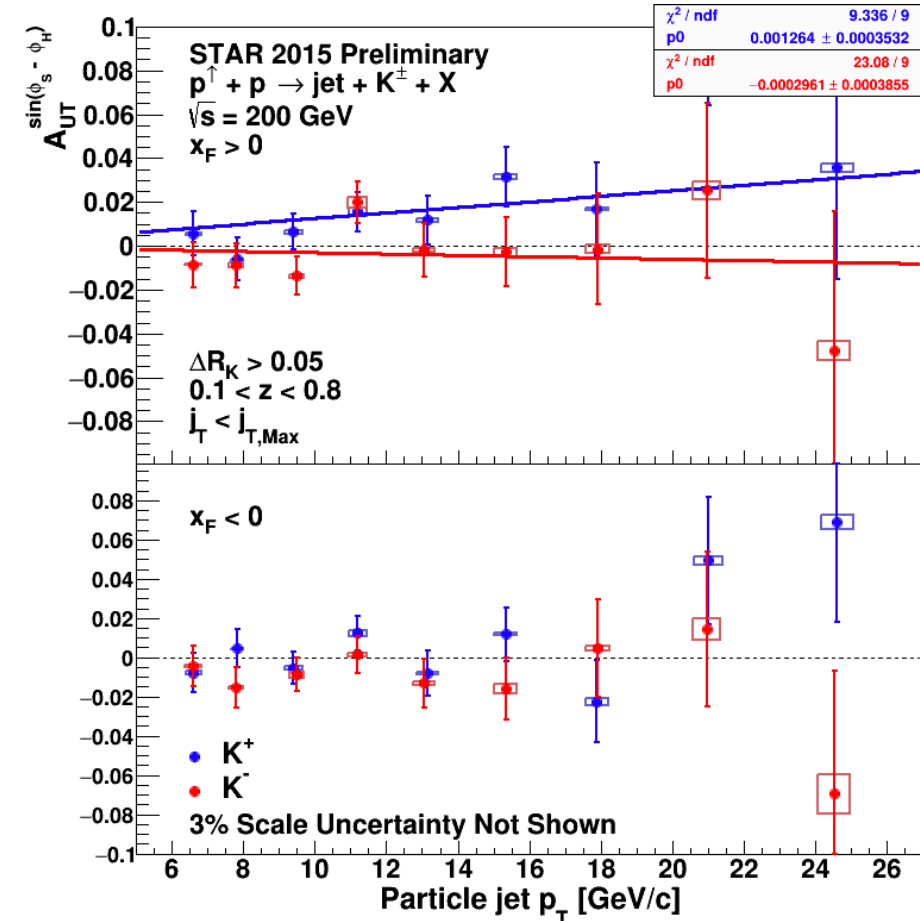
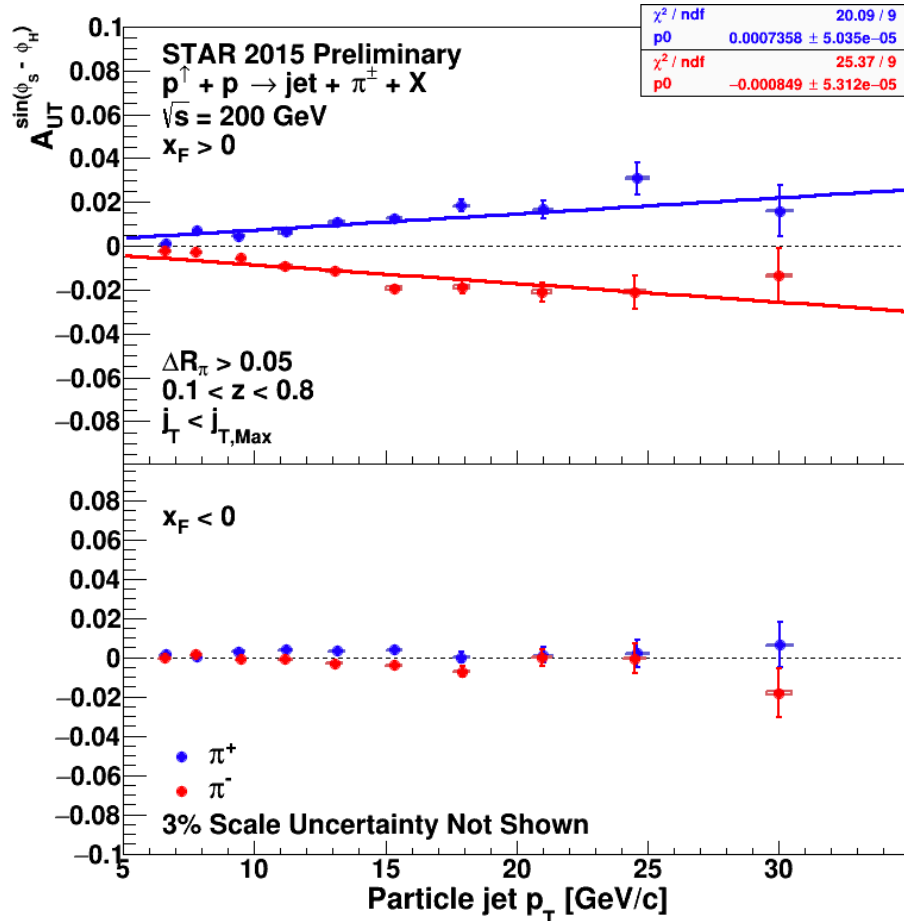
# Conclusion

- We present several new measurements of transverse single-spin asymmetries from inclusive jet and charged mesons inside jets at 200 GeV pp collisions;
  - Collins effect for  $\pi^\pm$  and  $K^\pm$
  - Collins-like effect for  $\pi^\pm$
  - $A_N$  for inclusive jets and for jets with high  $z$   $\pi^\pm$
- The inclusive jet and charged pion results are consistent with the previous STAR results and have smaller statistical and systematic uncertainties;
- STAR has a lot of additional spin data under analysis;
- STAR Forward Upgrade will provide unique and highly compelling opportunities to explore the QCD physics in the forward region.

# Back Up



# $K^\pm$ azimuthal distribution in jets



- $K^+$  shows positive asymmetries for forward jets, consistent within the currently large statistical uncertainties with the  $\pi^+$  asymmetries;